JOINT INSTITUTE FOR AERONAUTICS AND ACOUSTICS

027628

National Aeronautics and
Space Administration

Ames Research Center

Stanford University

JIAA TR 119

DEVELOPMENT OF AN APPARATUS FOR WIND TUNNEL DYNAMIC EXPERIMENTS AT HIGH-α

Nelson Pedreiro

Department of Aeronautics and Astronautics
Stanford University
Stanford, CA 94305

February 1997

Abstract

A unique experimental apparatus that allows a wind tunnel model two degrees of freedom has been designed and built. The apparatus was developed to investigate the use of new methods to augment aircraft control in the high angle of attack regime. The model support system provides a platform in which the roll-yaw coupling at high angles of attack can be studied in a controlled environment. Active cancellation of external effects is used to provide a system in which the dynamics are dominated by the aerodynamic loads acting on the wind tunnel model.

Acknowledgments

Contents

List of Figures

List of Tables

List of Symbols

b	wing span
C_μ	jet momentum coefficient, $\dot{m}_j V_j / q_\infty S_{ref}$
I_A	inertia of the suspension system about the γ-axis
I_M	model inertia in body frame
I_ϕ^R	inertia of the roll sub-system about the ϕ-axis
I_γ^S	inertia of the yaw sub-system about the γ-axis
g or **g**	acceleration of gravity
$\dot{m}_j$	jet mass flow rate
M_ϕ	moment about the ϕ-axis
M_γ	moment about the γ-axis
P	point defined by the intersection of the ϕ-axis and the γ-axis
p, q, r	roll, pitch and yaw rates respectively
q_∞	dynamic pressure, $\rho U^2/2$
S_{ref}	reference area, wing planform area
U	freestream velocity
V_j	air jet speed at the exit of the forebody slot
	wind tunnel model (body fixed) reference frame, centered at P
α	angle of attack
α_0	nominal incidence angle, equal to α when $\phi = \gamma = 0$
β	side slip angle
ϕ	first degree of freedom, roll
γ	second degree of freedom
ρ	air density

1   Introduction

The study of aircraft dynamics in the high angle of attack regime requires a description of the aerodynamics that includes both steady and transient effects. This involves modeling phenomena that are not completely understood such as separation and vortex breakdown. The main difficulties associated with flight at these regimes relate to vehicle control since flow separation results in decreased efficiency of conventional control surfaces and flow asymmetries result in the onset of lateral loads which cause departure from controlled flight. To address this problem various methods of active flow control have been suggested as a means to provide the necessary control augmentation [1-6,10,12]. For the most part the research in this area has consisted of characterizing the effects of various methods of flow control in the static loads acting on the vehicle and using this data, as an incremental effect, in simulations to demonstrate control augmentation. The problem with this approach is that either the transient effects are not incorporated in the model or at best they are approximated. There is also the issue of treating flow control devices as incremental effectors, *e.g.* assuming that stability derivatives of the vehicle are not a function of the actuation. Static data is sufficient to demonstrate that a certain device provides control authority, *i.e.* generates aerodynamic loads, but the issue of augmenting aircraft control is one of controllability and requires that the transient effects be taken into account. Given the difficulties in modeling the aerodynamics at these flight regimes a convincing proof of controllability can only be achieved trough an experimental demonstration.

The Department of Aeronautics and Astronautics at Stanford University has been involved in research in the field of Active Flow Control for several years. In particular the use of pneumatic means of flow control have been studied extensively [6-16]. Most of this effort has been conducted under the Joint Institute for Aeronautics and Acoustics (JIAA). In the subject of control augmentation at high angles of attack the work of Wong [9] is set apart because besides aerodynamic modeling and dynamic simulations it entailed an experimental demonstration in which the roll motion of a delta wing was controlled using pneumatic means of flow control as the only actuator. The success of his

experiments created an interested in conducting an experiment in which a wind tunnel model would have two degrees of freedom allowing a more complete investigation of the lateral-directional dynamics at high angles of attack.

In this report the development of an experimental apparatus that allows a wind tunnel model two degrees of freedom is presented. A model support system was designed and built in which dynamic experiments can be conducted to study the roll-yaw coupling at high angles of attack. Active cancellation of external effects is used to provide a system in which the dynamics is dominated by the aerodynamic loads acting on the wind tunnel model. The main objective achieved with the development of the apparatus is that the aerodynamic phenomena can be characterized, including transient effects, and new control augmentation techniques can be verified experimentally in a controlled and repeatable environment. In this way the validity of assumptions regarding the modeling of the aerodynamics and how it is affected by the use of flow control devices can be determined.

In addition to describing the design and operation of the experimental apparatus this report contains detailed data on sensor and actuator calibration and on the geometry and mass and inertia properties of the two degrees of freedom model support system. In this way all of the information necessary to operate, maintain and modify the experimental apparatus is contained in this document.

2   Wind Tunnel

The two degrees of freedom apparatus was designed for use in the low speed wind tunnel of the Aeronautics and Astronautics Department at Stanford University. The top view of the closed circuit wind tunnel is shown in Figure 1. The maximum freestream speed at the center line of the test section is 60 m/sec. The air speed is controlled by a variable speed motor to which a variable pitch fan is attached. Screens are located upstream of the test section and reduce the mean turbulence level at the test section to approximately 0.1% [9]. Three independent measurements are available of the freestream air speed obtained from the difference in the static pressure from two stations in the contraction and from two Pitot static tubes located in the upstream portion of the test section.
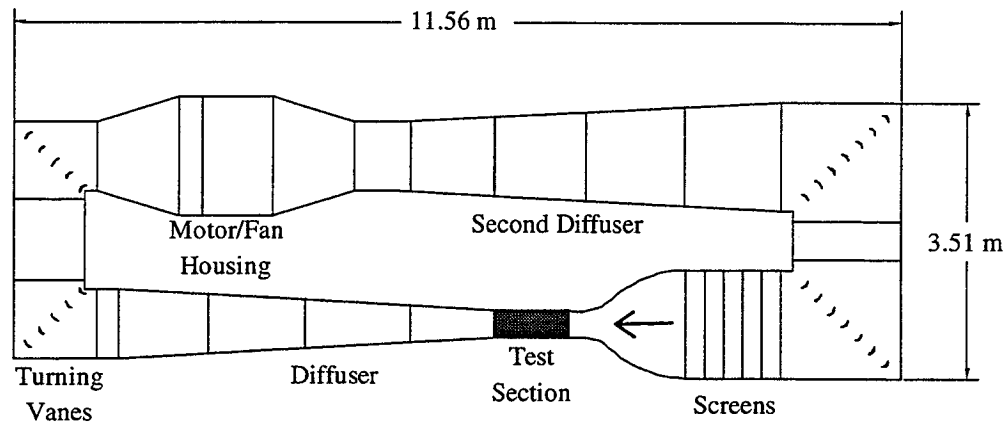
Figure 1: Top view of the wind tunnel.

Test section dimensions are: 0.45m X 0.45m X 0.91m, width, height and length respectively. It consists of a welded cast-iron frame. The bottom wall is made of sheet metal and top and side walls are made of plexiglass. The entire section is mounted on a cast-iron cart with castors and can be attached or removed from the rest of the wind tunnel. When in place, the test section is bolted to the exit of the tunnel contraction section.

3   Wind Tunnel Model

The development of the two degrees of freedom model support system occurred under the active flow control research initiative of the JIAA. As such a wind tunnel model consisting of a generic tailless fighter configuration and equipped with slots that allow the injection of air tangentially to the forebody was used as a baseline model in the development of the apparatus. This baseline model configuration, shown in Figure 2, has a sharp leading edge, 60 degree sweep angle delta wing, and a cone-cylinder fuselage[1]. The model has no movable control surfaces and slots through which blowing is applied are located on both sides of the forebody. Air is provided to the forebody plena through flexible tubing that enters the model through the rear end of the fuselage.
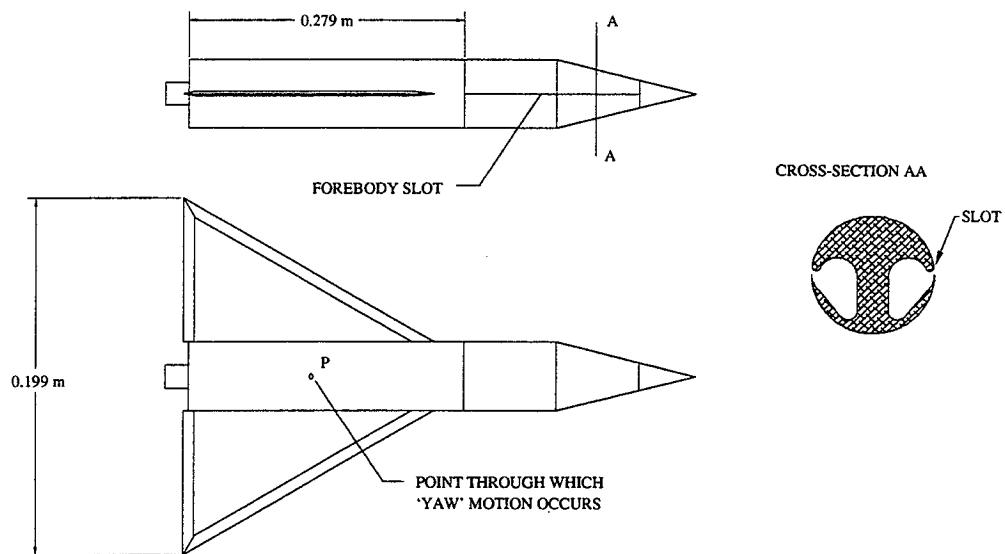
Figure 2: Wind tunnel model used as baseline in the design of the apparatus

Details on the dimensions of the model as well as the geometry of the slots are given in Appendix A. Mass, center of mass, and inertia properties of the model are also included as these quantities are required for the dynamic experiments. For completeness the characteristics of other available model configurations are also listed in the appendix.

4

4   Air Injection System

The air injection system controls the amount of air that is injected trough the forebody slots and consequently changes the flow and the aerodynamic loads acting on the model. An overall understanding of the air injection system is necessary because in the context of the research in Active Flow Control it operates in conjunction with the model suspension and is the only means of controlling the two degrees of freedom system since the model has no movable control surfaces.

The amount of air that is injected is quantified by the jet momentum coefficient, C_μ , defined as:

$$C_\mu \equiv \frac{\dot{m}_j V_j}{q_\infty S_{ref}} \qquad (1)$$

where $\dot{m}_j$ is the jet mass flow rate through the slot , V_j is the jet velocity at the exit of the plenum, q_∞ is the freestream dynamic pressure, and S_{ref} is the reference area (wing planform area).

Air is provided to the model through flexible tubing. Two servo-valves[1] are used to vary the amount of injected air on both plena independently. Specially designed flowmeters are used to measure the mass flow rate from which the jet momentum coefficient can be calculated. A closed loop control system is used to control the amount of air that is injected through each slot on the model. Figure 3 shows the block diagram for the closed loop control of C_μ. Feedforward is used to compensate for the non-linear characteristic of the valves and feedback control is used to generate adequate transient C_μ response and reject errors caused for example by pressure fluctuations on the source line. A detailed description of the servo valves and flowmeters is presented in Appendix B.

---

[1] Designed by Dr. Grant S. Wong [9]; machined by Mr. Tom Hasler (Former Aero/Astro Machine Shop).
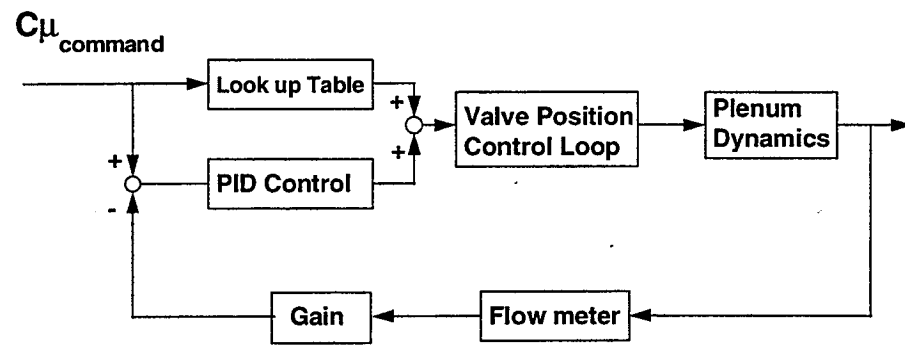
Figure 3: Closed loop control of the jet momentum coefficient, C_μ.

5   Model Support System

In this section the two degrees of freedom model support system is described. The objectives of designing and constructing such a suspension system are summarized and a discussion of the design approach is presented. The equations of motion for the two degrees of freedom system are included. Characteristics of the sensors and actuators used in the apparatus, as well as, parameters that characterize the support system are also presented. Detailed mechanical design drawings and assembly drawings are included in Appendix C.

5.1   Conceptual Design and Overall Configuration

The design of the apparatus was motivated by the need to conduct wind tunnel dynamic experiments to study aircraft control augmentation in the high angle of attack regime. Of particular interest was the use of pneumatic means of active flow control to improve the lateral-directional dynamics of the vehicle. To reach this goal an apparatus which allows the wind tunnel model two degrees of freedom was designed and built. The choice of degrees of freedom was determined by the particular interest in studying the roll-yaw coupling at high angles of attack and by implementation issues, such as: system complexity and cost, and compatibility with existing hardware.

The implemented degrees of freedom, ϕ and γ, are an approximation to roll and yaw. ϕ is a rotation about the longitudinal axis of the model and γ is a rotation about a perpendicular axis as illustrated in Figure 4. The approximation to roll-yaw is represented by relating $\dot{\phi}$ and $\dot{\gamma}$ to the roll, pitch and yaw rates, p, q, and r respectively:

$$p = \dot{\phi}$$
$$q = \dot{\gamma}\ \sin\phi$$
$$r = \dot{\gamma}\ \cos\phi \tag{2}$$
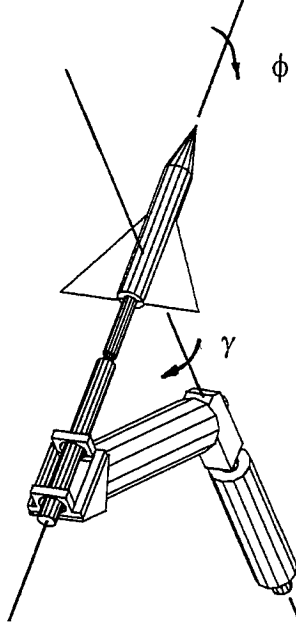
Figure 4: The two degrees of freedom. Approximation to roll-yaw.

The apparatus degrees of freedom, ϕ and γ, relate to the angle of attack, α, and the side slip angle, β, through the following expressions:

$$\cos\alpha \cos\beta = \cos\alpha_0 \cos\gamma$$

$$\sin\beta = \sin\alpha_0 \sin\phi - \cos\alpha_0 \sin\gamma \cos\phi$$

$$\sin\alpha \cos\beta = \sin\alpha_0 \cos\phi + \cos\alpha_0 \sin\gamma \sin\phi \qquad (3)$$

where α_0 is used to represent the nominal incidence angle, *i.e.* the angle between the longitudinal axis of the model and the freestream velocity for $\phi=\gamma=0$.

Once the two degrees of freedom were defined the overall configuration of the apparatus was determined driven by the following guidelines:

- Apparatus interference with the flow in the test section should be minimal.

- The aerodynamic loads acting on the model should dominate the dynamics of the system.

- The apparatus stiffness should be selected so that aeroelastic effects can be neglected.

The resulting system is shown in Figure 5 mounted to the wind tunnel test section. The wind tunnel model is attached to a shaft (roll shaft) mounted on bearings which allows rotation about the longitudinal axis of the model. The roll shaft support is connect to a second shaft ('yaw' shaft), also mounted on bearings, through a mechanical arm which runs parallel to the bottom wall of the test section. Only part of the roll shaft enters the test section resulting in a clean aerodynamic configuration in which the test section blockage caused by the apparatus is approximately 1%. The diameter and wall thickness of the roll shaft and mechanical arm were determined to provide a stiff model supporting structure. Their dimensions based on the linear and angular deflections at the center of mass of the model caused by 1.2 times (design margin) the maximum expected aerodynamic loads acting on the model when the tunnel is run at its maximum speed.
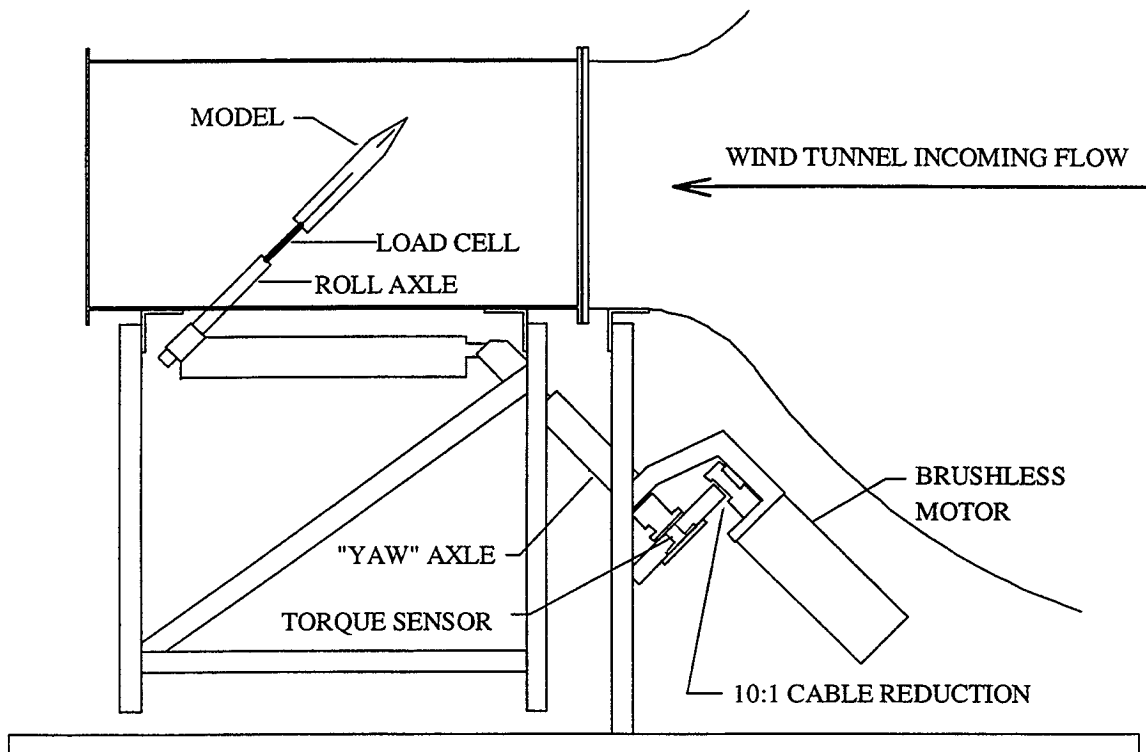
Figure 5: Side view of test section and two degrees of freedom model support system.

9

Experiments and simulations [15,16] indicated that the inertia and gravity restoring moment of the support system were large effects that dominated its dynamic behavior. To address this problem a system to provide active cancellation of these large external effects was designed and built. The active cancellation system has sensors that measure angular position and acceleration about the γ-axis from which a torque command is generated and sent to a motor connected to the 'yaw' shaft. The motor applies a torque to the 'yaw' shaft that cancels the torque due to gravity and inertia of the apparatus. A picture of the test section with a wind tunnel model mounted to the two degrees of freedom model support system is shown in Figure 6.
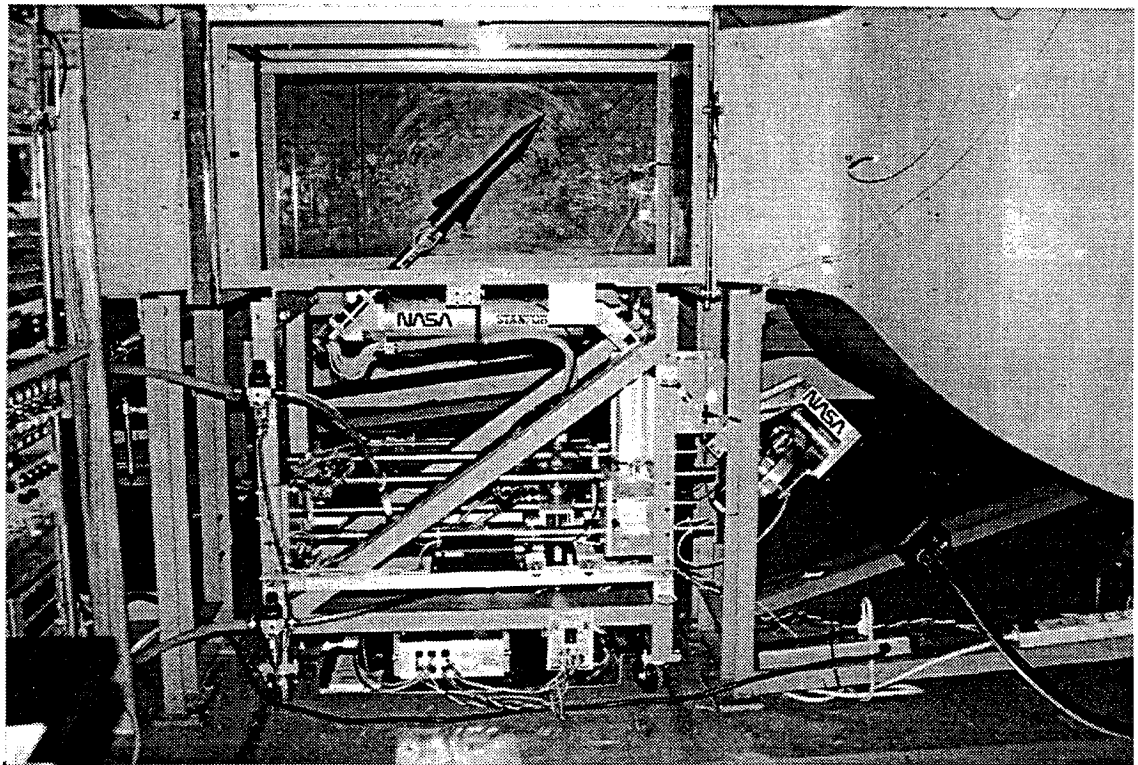
Figure 6: View of wind tunnel facilities and experimental apparatus.

Mechanical constraints limit the degrees of freedom to the following ranges: $|\phi| < 105$ degrees and $|\gamma| < 30$ degrees. It is possible to vary the nominal incidence angle, α_0, in the range from 37 to 55 degrees. Provisions exist to lock each of the degrees of freedom independently at any position within the envelope of the apparatus. This feature is used during static experiments.

5.2 Implementation of the Two Degrees of Freedom

The main components of the roll system are shown in Figure 7. Also shown is the baseline wind tunnel model mounted to the system. All parts are made of aluminum 6061-T6 except for the roll shaft and the bearings which are made of steel. The model is mounted to the roll shaft trough a six-component force-torque sensor[1] which provides static and dynamic measurements of the loads acting on the model. The roll shaft is mounted on precision bearings[2] to allow rotation about the longitudinal axis of the model. A low friction precision potentiometer[3] is used to measure the roll angle. For the active flow control experiments it is necessary to provide pressurized air to the plena of the wind tunnel model. This is accomplished by routing the air supply tubing (eight 3/16 inch external diameter flexible tubes) through the interior of the roll shaft. The tubing enters the shaft at its end close to the potentiometer and emerges at the other end of the shaft where it is routed around the force-torque sensor and connected to special ports at the rear end of the model.
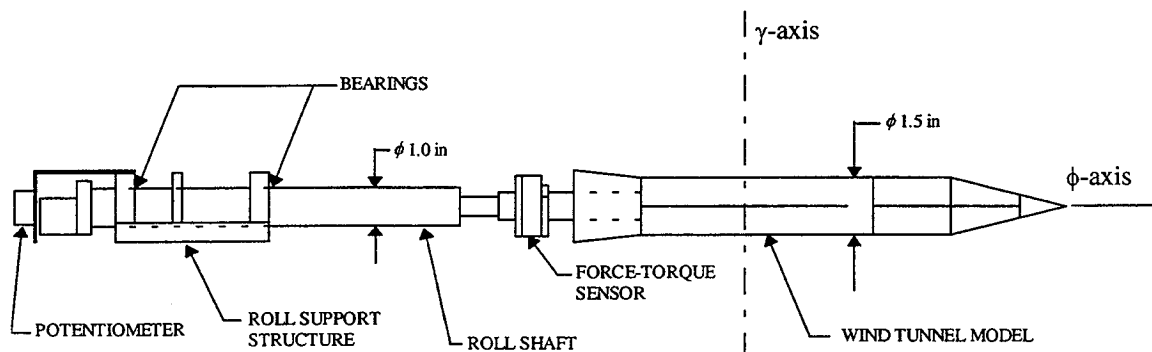
Figure 7: Implementation of rotation about the ϕ-axis.

---

[1] Mini 90N/4.2Nm. Serial #FT3253. Assurance Technologies, Inc. Garner, NC 27529.

[2] Kaydon KAA10CL4 ball bearing. Kaydon Corporation, Muskegon, Michigan 49443 USA.

[3] Precision potentiometer MKV-F78S. Conductive plastic RESISTOFILM®. New England Instrument Company. Woonsocket, RI 02895-1129.

The inertia of the moving parts about the ϕ-axis excluding the model is labeled I_ϕ^R and is listed in Table 1. It includes contributions from the roll shaft, bearings, collars, fixtures, potentiometer and air supply tubing. Disturbance torques about the ϕ-axis are caused by the friction on the bearings and potentiometer and springiness of the air supply tubing. Stiction does not occur because the unsteady aerodynamics at high angles of attack has a dither like effect on the system. Experiments showed that the moment due to friction could be represented by:

$$M_\phi^F = -C_F \dot{\phi} \qquad (4)$$

where C_F is a constant determined experimentally and is listed in Table 1. The moment due to the springiness of the air supply tubing, M_ϕ^T, depends on the configuration used for the tubing. For the configuration shown in Figure 6 this moment is less than 0.002 Nm for $|\gamma| < 35$ degrees [16].

Figure 8 illustrates the implementation of the second degree of freedom, γ. For completeness the roll system and the active cancellation system are also shown in the figure. Rotation about the γ-axis is made possible by a mechanical assembly consisting of two co-axial shafts connected through bearings[1]. The inner shaft can rotate while the outer shaft is fixed to the test section. The roll-yaw connecting structure is mounted to the inner shaft and can rotate about the γ-axis. In the figure the location of the bearings and of the torque sensor used to connect the yaw shaft to the active cancellation system are indicated by shaded areas.

---

[1] BERG Ball Bearings - #B1-21 - UNSHIELDED
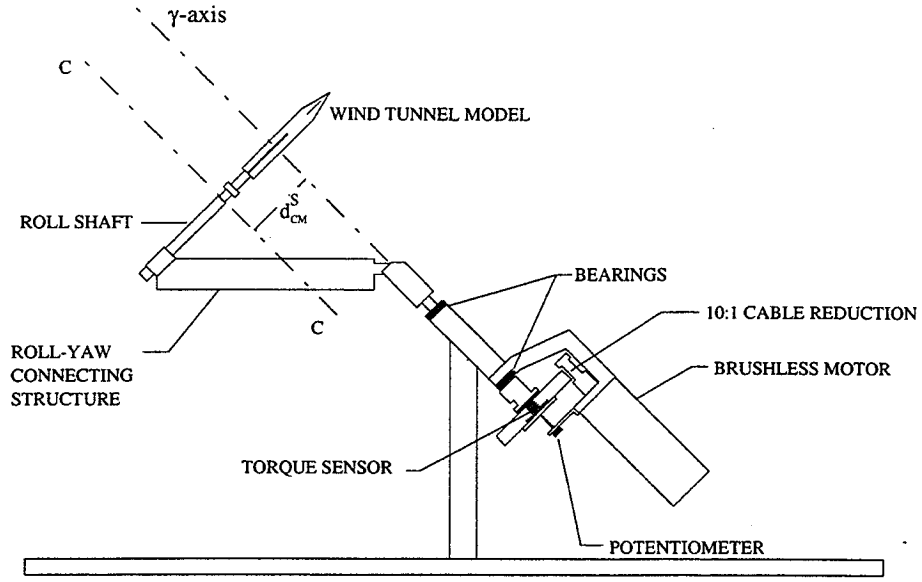
Figure 8: Implementation of rotation about the γ-axis.

Given the geometry and mass distribution of the supporting structure a gravity restoring moment exists about the γ-axis which is given by:

$$M_\gamma^G\big|_S = -m_S g\, d_{CM}^S \sin(\gamma) \tag{5}$$

where the quantities in the equation refer to a system S formed by the moving parts of the support system about the γ-axis, *i.e.* m_S is the mass of the moving parts of the support system and does not include the model and d_{CM}^S is the distance from the center of mass of S to the γ-axis. In the equation g represents the acceleration of gravity. In Figure 8 the center of mass of S is at some point on line CC. Measured values for m_S and d_{CM}^S as well as for the inertia of the support system about the γ-axis, I_γ^S, are given in Table 1. A potentiometer, identical to the one used to measure the roll angle, is used to provide a measure of the second degree of freedom γ.

13

The moment about the γ-axis due to friction in the bearings and potentiometer, M_γ^F, is given by:

$$M_\gamma^F = -D_F \dot{\gamma} \qquad (6)$$

where the constant D_F was determined experimentally and is listed in Table 1.

Characteristic	Value	Units
I_ϕ^R	$(8.4 \pm 0.5) \times 10^{-5}$	$Kg\,m^2$
m_S	3.91 ± 0.01	Kg
d_{CM}^S	$(119.6 \pm 0.8) \times 10^{-3}$	m
I_γ^S	$(155.8 \pm 1.0) \times 10^{-3}$	$Kg\,m^2$
C_F	$(1.1 \pm 0.3) \times 10^{-3}$	$Nm\,sec$
D_F	$(8.5 \pm 2.6) \times 10^{-3}$	$Nm\,sec$

Table 1: Main parameters of the model support system.

5.3 Equations of Motion

The equations of motion of the two degrees of freedom system are:

$$I_{M_x} \ddot{\phi} + (I_{M_z} - I_{M_y}) \sin\phi \cos\phi \dot{\gamma}^2 + I_{M_{xz}} \cos\phi \ddot{\gamma} = M_\phi$$

$$(I_A + I_{M_y} \sin^2\phi + I_{M_z} \cos^2\phi)\ddot{\gamma} + (I_{M_y} - I_{M_z})2\sin\phi\cos\phi\dot{\phi}\dot{\gamma}$$

$$+ I_{M_{xz}}(\ddot{\phi}\cos\phi - \dot{\phi}^2 \sin\phi) = M_\gamma \qquad (7)$$

where I_M is represents the inertia characteristics of the model with respect to a body-fixed frame $(XYZ)_M$ centered at point P, the intersection of the ϕ and γ axis, with X oriented along the longitudinal axis of the model, Z in the vertical plane of symmetry of the model oriented towards the pressure side and Y given by the cross-product: Z x X. I_A is

14

the inertia of the support about the γ-axis including the inertia of the motor times N^2, where N:1 is the reduction ratio between the 'yaw' shaft and the motor shaft. M_ϕ is the moment acting about the longitudinal axis of the model, ϕ-axis, and M_γ is the moment about the γ-axis.

As discussed in Section 5.1 an objective in designing the apparatus was that the dynamic properties of the support system should not dominate the dynamic response of the model. One of the effects of the apparatus is represented on left hand side of Equation 7 by a term proportional to the inertia of the support system. Because this inertia is much larger than the inertia of the model (50 times larger than the inertia of the baseline model in yaw) this term dominates the response about the γ-axis and degenerates the dynamics of the system. Other effects of the apparatus can be identified by a closer examination of the right hand side of Equations 7. Expressions for the moments about the ϕ and γ axis can be written as:

$$M_\phi = M_\phi^A + M_\phi^T + M_\phi^F$$
$$M_\gamma = M_\gamma^A + M_\gamma^T + M_\gamma^F + M_\gamma^G \tag{8}$$

where superscripts A, T, F and G indicate the origin of the moments: Aerodynamic, Tubing, Friction and Gravity respectively. It is seen that the springiness of the air supply tubing and the friction from the bearings and potentiometer affect both the motion about the ϕ and γ axis, and a gravity restoring moment affects the motion about the γ-axis only. Experiments demonstrated that the effects of the tubing and friction are small when compared to the aerodynamic loads [11,16], *i.e.* these effects do not dominate the dynamic response of the system. Moreover these effects are known, *e.g.* Equations 4 and 6, and can be accounted for if necessary. For these reasons neither the friction nor the spring effects are canceled about the ϕ-axis and the friction moment is not canceled about the γ-axis. On the other hand, cancellation of the gravity restoring moment and inertia of the apparatus was necessary as these are large effects that dominate the response of the

system about the γ-axis. The concept for the active system designed and built to cancel these effects was presented in Section 5.1 and a detailed description of this system given in the next section.

5.4   Active Cancellation System

The active cancellation system uses measurements of the angle γ and the angular acceleration $\ddot{\gamma}$ to compute the torque that should be applied to the γ-shaft to cancel the moments due to inertia, gravity and tube springiness about the γ-axis. This computed torque is sent to a torque closed loop control system which consists of an electric brushless motor[1] connected to the 'yaw' shaft through a 10:1 cable reduction[2] and a specially designed torque sensor that provides a precise measure of the torque applied to the system. The logic for the torque control loop consists of a notch filter[3] and is implemented in a micro computer equipped with A/D and D/A converters. The computer program is written in C and its listing is given in Appendix D. Figure 9 illustrates the operation of the active cancellation system in block diagram form.
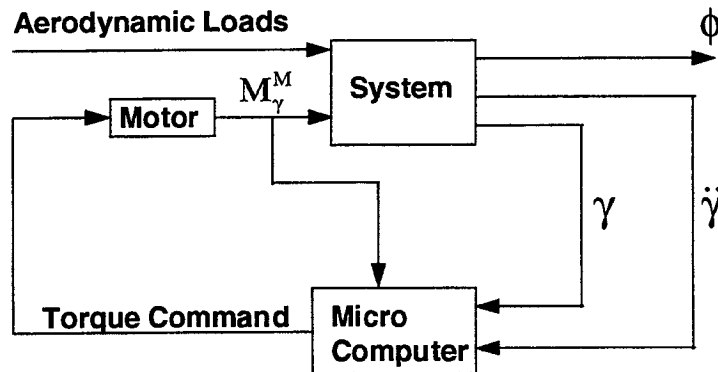
Figure 9: Concept and operation of the active cancellation loop.

---

[1] Electro-Craft Brushless Servo System: DM-30 drive, S-4075-R-H00AA motor. Reliance Motion Control, Inc. Eden Prairie, MN 55344.

[2] A simulation of the natural motion of the model free from any effect of the apparatus and for the tunnel running at maximum speed was used to calculate the torque required from the motor. This result indicated that a reduction was necessary to provide enough torque to cancel the inertia of the apparatus. A cable reduction was selected because of its linear characteristics and smoothness.

[3] The notch filter was required to stabilize the lowest resonance mode of the structure at 33 Hz.

The torque commanded to the motor is given by:

$$M_\gamma^{M_c} \equiv I_A \hat{\ddot{\gamma}} + K_T^\gamma \hat{\gamma} + K_G \sin \hat{\gamma} \qquad (9)$$

where $\hat{\gamma}$ and $\hat{\ddot{\gamma}}$ are estimates of the angle γ and the angular acceleration $\ddot{\gamma}$. Using M_{error} to represent the errors in the torque control loop the actual torque applied to the shaft can be written as:

$$M_\gamma^M \equiv M_\gamma^{M_c} + M_{error} \qquad (10)$$

Substituting the various expressions for the moments into Equation 7, and adding to the moment about the γ-axis the torque due to the motor results:

$$I_{M_x} \ddot{\phi} + (I_{M_z} - I_{M_y}) \sin \phi \cos \phi \dot{\gamma}^2 + I_{M_{xz}} \cos \phi \ddot{\gamma} = M_\phi^A - C_F \dot{\phi} - K_T^\phi \phi$$

$$I_A (\ddot{\gamma} - \hat{\ddot{\gamma}}) + (I_{M_y} \sin^2 \phi + I_{M_z} \cos^2 \phi) \ddot{\gamma} + (I_{M_y} - I_{M_z}) 2 \sin \phi \cos \phi \dot{\phi} \dot{\gamma}$$

$$+ I_{M_{xz}} (\ddot{\phi} \cos \phi - \dot{\phi}^2 \sin \phi) = M_\gamma^A - D_F \dot{\gamma} - K_T^\gamma (\gamma - \hat{\gamma}) - K_G (\sin \gamma - \sin \hat{\gamma}) + M_{error} \qquad (11)$$

The angle γ is measured directly through the use of a potentiometer. This measured value, γ_m, is used as the estimate for γ, i.e. $\hat{\gamma} \equiv \gamma_m$. Two high precision linear accelerometers[1] are mounted to the γ-axle. When $\gamma=0$ they are located in the vertical plane that contains the γ-axis and are mounted at equal distances in opposite sides of the γ-axle as shown in Figure 10. Adding the signals from the two accelerometers cancels the effect of specific weight and provides a signal that is proportional to $\ddot{\gamma}$. This measurement of the angular acceleration, $\ddot{\gamma}_m$, is accurate to 0.01 rad/sec^2 and is used as the estimate value for that quantity, i.e. $\hat{\ddot{\gamma}} \equiv \ddot{\gamma}_m$. In this way the torque required to cancel

---

[1] Systron Donner 4310A-1-P116 Linear Servo Accelerometer. Systron Donner Company. Inertial Division. Concord, CA 94518.

17

the external effects is computed according to Equation 9, using the measurements for γ and $\ddot{\gamma}$ as their estimates.
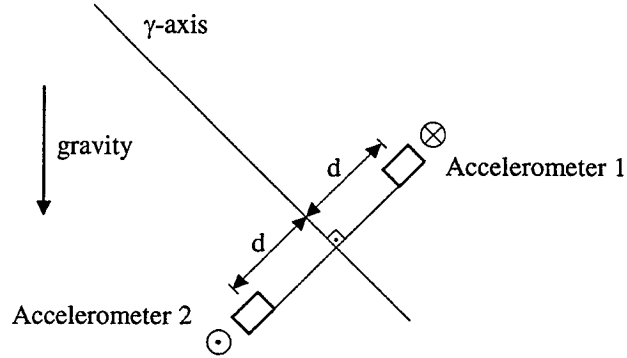
Figure 10: Measurement of angular acceleration $\ddot{\gamma}$ using two linear accelerometers.

The cancellation is not perfect due to limitations of the actual implementation. Errors occur in the torque closed loop control and in the measurements of γ and $\ddot{\gamma}$. To access the performance of the cancellation loop the error between the commanded torque, as given by Equation 9, and the actual torque measured during the natural motion of the system was compared to the unsteady aerodynamic moment about the γ-axis, M_γ^A [16].

The torque due to errors in the cancellation loop resulted as large as 14% of the aerodynamic moment, mostly due to a lightly damped resonant mode at approximately 33 Hz. This indicates that although the aerodynamics is the main factor determining the motion of the system the errors in the cancellation loop need to be included if an accurate description of the system dynamics is sought. The main reason for the large errors in the cancellation loop is the large inertia of the support system[1] which requires the application of a large torque to the γ-axis. This means that even a small percentage error in the applied torque translates into a significant moment as compared to the aerodynamic loads. For these reasons when using the equations of motion for the two degrees of freedom system either the moment applied by the motor should be explicitly included or the cancellation error should be treated as a disturbance.

---

[1] The inertia of the support about the γ-axis is approximately 50 times the inertia of the model in yaw.

5.5   Sensor and Actuator Characteristics

As discussed in the previous sections the dynamic model support system includes various sensors and an actuator which form an integral part of the apparatus and are required for it to function properly. These sensors and actuator are listed in Table 2 with a description of their functionality. A discussion of each of these devices is presented in the following sections including their physical characteristics and calibration.

Application	Sensor / Actuator
Measurement of the two degrees of freedom, ϕ and γ	ECONOPOT® Precision potentiometer MKV-F78SC103. Conductive plastic RESISTOFILM®. New England Instrument Company. Woonsocket, RI 02895-1129.
Measurement of the angular acceleration, $\ddot{\gamma}$	Systron Donner 4310A-1-P116 Linear Servo Accelerometer. Systron Donner Company. Inertial Division. Concord, CA 94518.
Measurement of the torque applied to the γ-axle	Custom designed torque sensor.
Measurement of the loads acting on the model	Mini 90N/4.2Nm. Serial #FT3253. Assurance Technologies, Inc. Garner, NC 27529.
Torque cancellation	Electro-Craft® Brushless Servo System: DM-30 drive, S-4075-R-H00AA motor. Reliance Motion Control, Inc. Enden Prairie, MN 55344.

Table 2: Sensors and actuator used in the dynamic model support system.

5.5.1   Potentiometers

Precision potentiometers are used to measure the two degrees of freedom ϕ and γ by measuring the roll and 'yaw' shaft angles. The selected sensor is a 10 KΩ low friction potentiometer, model MKV-F78SC103, manufactured by New England Instrument Company [17]. Its main characteristics are summarized in Table 3. A drawing of the sensor with its dimensions is shown in Figure 11.

Parameter	Value
Total resistance	10 KΩ
Linearity	0.25 %
Theoretical electrical travel	340 deg.
Output smoothness	0.15 %
Life expectancy	20×10^6 cycles
Resolution	essentially infinite
Power rating .	1 Watt at 70°C
Insulation resistance	1000 Megohms min. at 500 VDC
Dielectric withstanding voltage	750 Volts RMS
Standard torque	0.5 oz.-in. max.
Operating temperature	−65°C to +125°C

Table 3: Characteristics of the MKV-F78SC103 potentiometer.
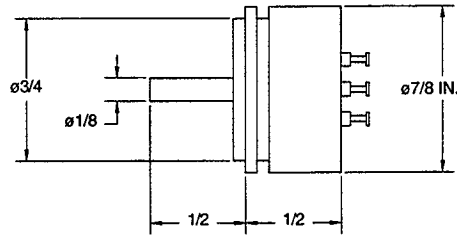
Figure 11: Dimensions of the potentiometer used for measurements of ϕ and γ.

Calibrations were performed for the measurements of the angles ϕ and γ obtained using the potentiometers connected to the proper excitation circuitry. The calibration procedure consisted of mounting the potentiometer to an aluminum plate and connecting a compass to its shaft. Data were recorded for the compass readings versus the potentiometer output in Volts for various angles and a least squares fit was used to determine the gain from output voltage to angle. Calibration results for the measurement of ϕ and γ are shown in Figures 12 and 13 respectively. The plots show both the experimental data and the result of the least squares fit.
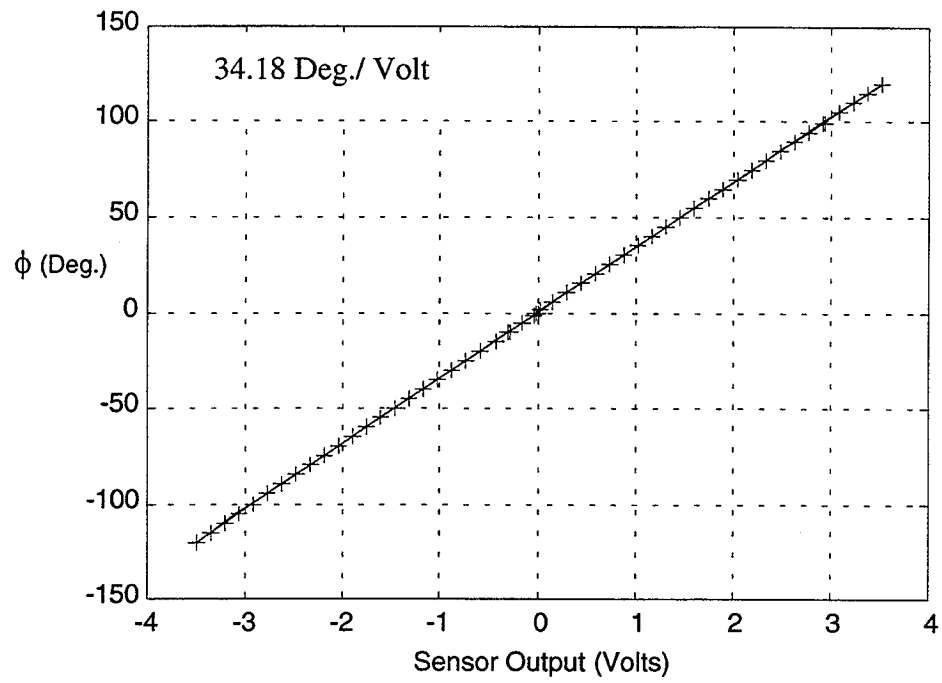
Figure 12: Calibration results for the measurement of the angle φ.
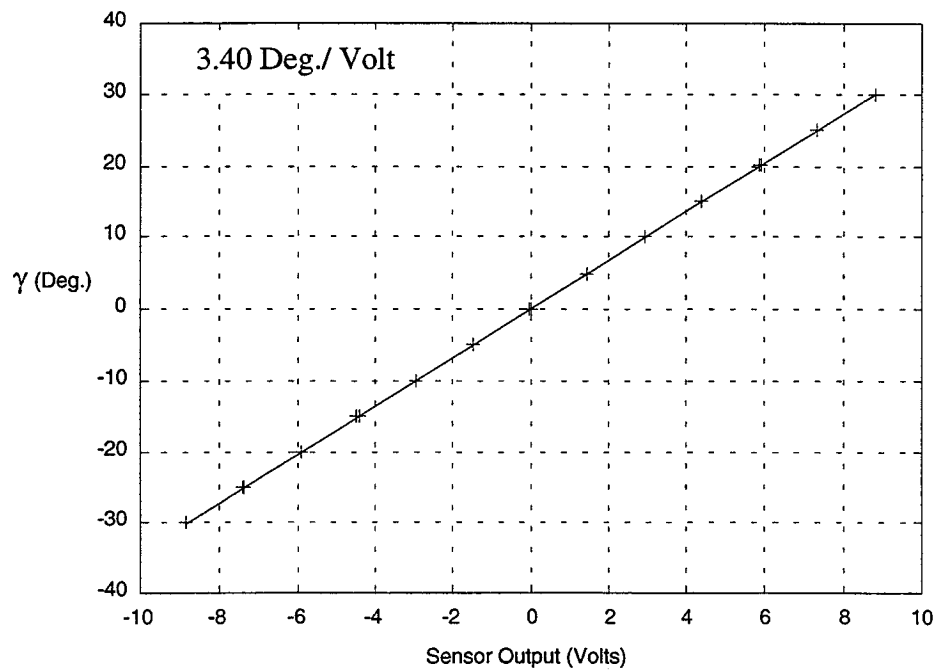
Figure 13: Calibration results for the measurement of the angle γ.

5.5.2 Accelerometers

The measurement of the angular acceleration about the γ-axis is obtained by adding the output of two linear accelerometers arranged as described in Section 5.4. Two identical high accuracy linear servo accelerometers, model 4310A-1-P116, manufactured by Systron Donner Inertial Division are used in the apparatus. The dimensions and configuration of the accelerometers are shown in Figure 14. Physical properties and accuracy parameters are summarized in Table 4.
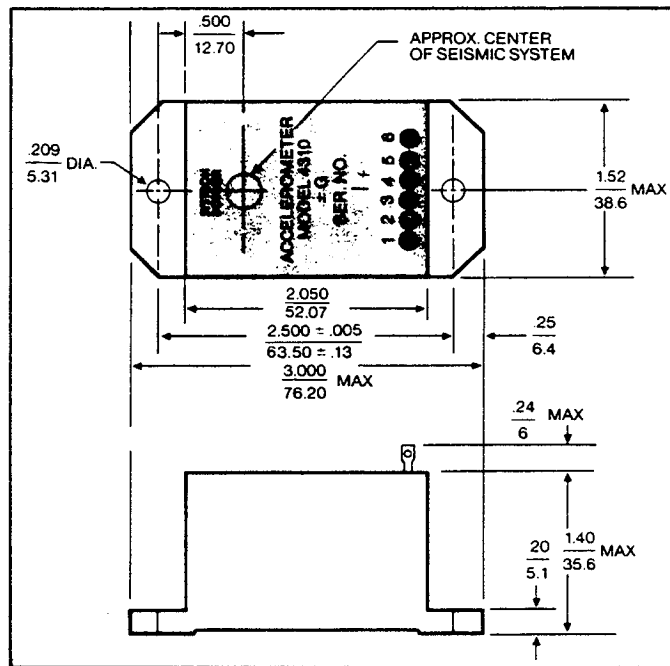
Figure 14: Systron Donner model 4310A-1-P116 linear servo accelerometer.

Parameter	Value
Range	± 1.0 g
Input power	± 15 VDC at 10 mA max.
Voltage output	± 7.5 VDC full scale
Output Impedance	5 KΩ
Output current	3 mA full range
Electrical connections	6 solder terminals
Case alignment (each axis)	< 1 deg. to true sensitive axis
Weight	128 grams
Temperature range	$-40°$C to 93°C operating
Non-linearity	< 0.05% of full range
Hysteresis and non-repeatability	< 0.02% of full range
Resolution	< 0.001% of full range
Zero output (null)	< 0.05% of full range
Temp. coeff. of null	< 0.0018% per °C
Output noise	< 0.0075 VRMS
Cross-axis sensitivity	< 0.002 g / g
Scale factor	< 0.018% per °C
Natural frequency	50-250 Hz
Damping ratio at 22°C	0.7 $\pm$ 0.1 (standard)

Table 4: Characteristics of the Systron Donner 4310A-1-P116 linear servo accelerometer.

The angular acceleration $\ddot{\gamma}$ is proportional to the sum of the output signals from the two linear accelerometers. The center of each accelerometer seismic system is located at 2.85 inches from the γ-axis and the calibration for the filtered output of each of the accelerometers resulted equal to 4.16 Volt/g. Using this results the gain between the sensor output (sum of the outputs from each accelerometer) and the angular acceleration $\ddot{\gamma}$ is 16.29 (rad/sec^2)/Volt. To verify this result the motor of the active cancellation system was used to impart a harmonic motion to the 'yaw' system and data was recorded for the time histories of the outputs of the accelerometers and potentiometer. The signal of the potentiometer was processed (differentiated twice and smoothed) to generate a measure of the angular acceleration which was compared to the measurement of $\ddot{\gamma}$ from the accelerometers. This procedure was repeated for various frequencies of the harmonic

oscillation and the average result obtained, 16.3 (rad/sec^2)/Volt, compares well with the initial calibration.

5.5.3 Torque Sensor

The torque sensor connects the active cancellation system to the 'yaw' shaft and provide an accurate measure of the torque applied by the cancellation system to the γ-axis. It was specially designed and built for this application. The mechanical component of the sensor is shown in Figure 15, it is built from Aluminum 6061-T6 and the flanges at both ends are used to connect the sensor to the rest of the system. The central portion between the flanges is where the sensing elements are located, it has a thin wall square cross-section.

Figure 15: Torque sensor mechanical component.

24

Semiconductor strain gages[1] are used to provide a large dynamic range on the torque measurement. Four gages are bonded, one at each surface of the square section at 45 degree angle, and connected to form a Wheatstone bridge, Figure 16. In the figure a, b, c and d represent the four strain gages and R their resistance, E_{IN} and E_{OUT} are the excitation and the output voltages respectively. An excitation voltage equal to 5 Volts is used and the output signal, E_{OUT}, is multiplied by a gain of 20 to provide a signal range of approximately ±8 Volts in the operational region of the sensor.
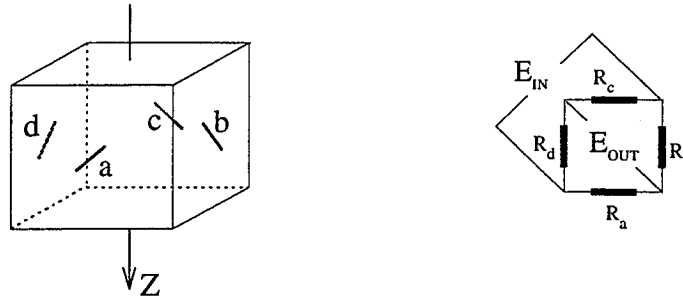
Figure 16: Strain gage configuration and Wheatstone bridge used in the torque sensor.

The sensor was designed to measure torque about the Z axis, T_z (shown in Figure 15), and to first order the sensor output is proportional to T_z. Data from calibration experiments and a least squares algorithm were used to determine the constant of proportionality. The results of the calibration and of the parameter fit are shown in Figure 17.

[1] Kulite semiconductor strain gages S/UDP-350-160 [18]. Kulite Semiconductor Products, Inc. Leonia, New Jersey 07605, USA.
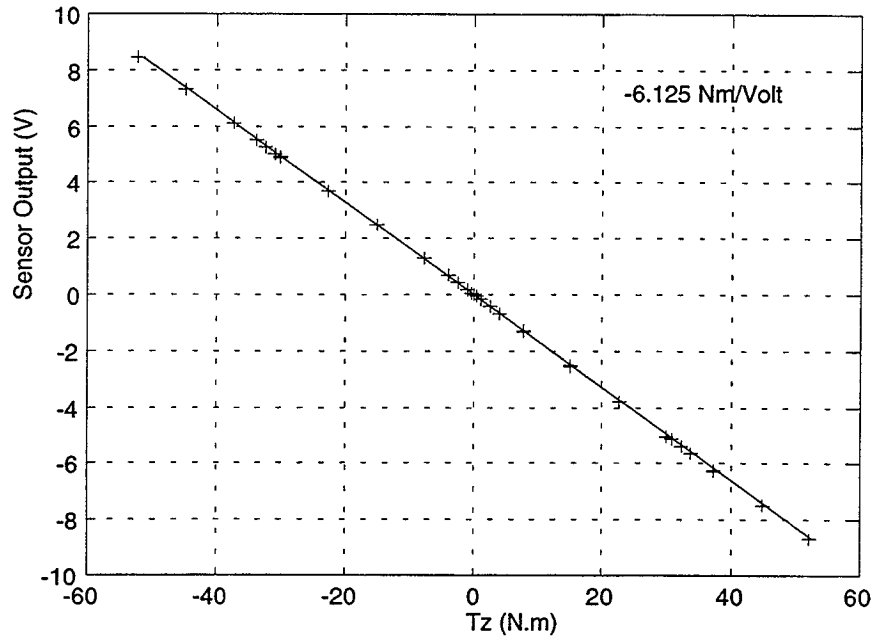
Figure 17: Torque sensor calibration results.

Because the sensor is subjected to forces and torques about the other two axis a calibration was conducted to determine the cross-coupling. The results of this calibration are summarized in Table 5, where the maximum errors in the sensor output caused by each of the other load components acting on the sensor are given. In the table subscripts X, Y and Z indicate the orientation (according to Figure 15) of the force and torque vectors **F** and **T** respectively. The total maximum error is approximately 1 % and is not compensated for.

Load Component Acting on Sensor	Sensor Output Error
$\mathbf{F}_X$	0.04 %
$\mathbf{F}_Y$	0.82 %
$\mathbf{F}_Z$	≈ 0
$\mathbf{T}_X$	0.01 %
$\mathbf{T}_Y$	0.24 %

Table 5: Maximum torque sensor errors due to cross-coupling.

The main characteristics of the torque sensor are summarized in Table 6.

Parameter	Value
Operational range	± 50 Nm
Linearity	1.1 %
Maximum load	± 210 Nm
Resolution	essentially infinite
Stiffness about the Z axis	2.015 x 10^4 Nm/rad
Excitation voltage	5 VDC
Maximum input voltage	5.9 VDC
Power rating	0.1 Watt

Table 6: Characteristics of the torque sensor.

5.5.4 Six-Component Force-Torque Sensor

A six component force-torque torque sensor[1] connects the wind tunnel model to the roll shaft and is used to provide static and dynamic measurements of the loads acting on the model. The sensor used is a standard model manufactured by Assurance Technologies, Inc. and comes calibrated from the factory with electronics and cables. For this application a custom calibration was conducted to adapt this off-the-shelf item to the range of loads to be measured in the wind tunnel. The configuration and dimensions of the sensor are shown in Figure 18.

---

[1] Mini 90N/4.2Nm. Serial #FT3253. Assurance Technologies, Inc. Garner, NC 27529. USA.
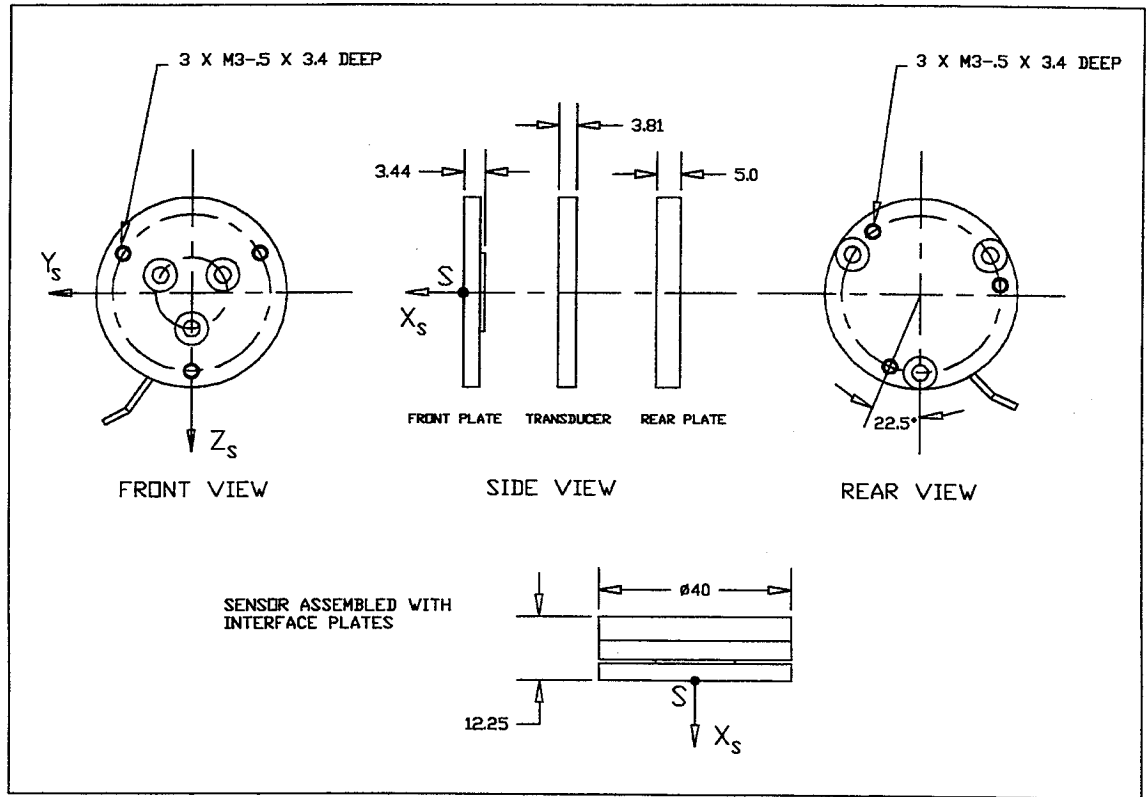
Figure 18: Configuration of the six-component force-torque sensor.

The sensor was evaluated by conducting an independent calibration which showed that, with exception of the axial force component, its measurements are accurate. The problem with the axial force component, force along X_s , is that the resolution is not adequate for the range of loads typical of the wind tunnel experiments. In spite of this fact this sensor was selected because the axial force component is not essential in the study of the lateral-directional dynamics of the system and because of the sensor low cost and the short lead time for delivery. The sensor maximum operational load and resolution are listed in Table 7, for each force-torque component with respect to reference frame $X_s Y_s Z_s$, defined in Figure 18, centered at point S on the sensor. More detailed data on the six-component sensor can be obtained from reference [19].

Force-Torque Component	Range	Resolution
Forces along Y_s and Z_s	± 90 N	0.045 N
Force along X_s	± 90 N	0.135 N
Moments about X_s, Y_s and Z_s	± 4.2 Nm	0.0011 Nm

Table 7: Characteristics of the six-component force-torque sensor.

5.5.5 Torque Motor

A servo system, consisting of a brushless motor and its drive, is used to provide the necessary actuation for the active cancellation described in Section 5.4 and is simply referred to as the torque motor. A low inertia brushless motor, model S-4075-R-H00AA, and a digital drive, model DM-30, both manufactured by Reliance Motion Control, Inc., are used to apply the necessary torque to the 'yaw' shaft. The main characteristics of the servo system are summarized in Table 8.

Parameter	Value
Rotor moment of inertia	0.00068 Kg m^2
Damping	0.068 Nm/Krpm
Friction torque	0.14 Nm
Max. continuous operating speed	3000 rpm
Continuous stall torque	10.2 Nm
Peak torque (at 25°C)	19.7 Nm
Sine wave torque constant (at 25°C)	0.74 Nm/A
Square wave torque constant (at 25°C)	0.81 Nm/A
Voltage constant	90 V/Krpm
Motor shipping weight	14.1 Kg
Motor envelope[1] (approximate)	121 x 121 x 324 mm
Motor shaft	19 mm DIA. x 50 mm

Table 8: Characteristics of the S-4075-R-H00AA / DM-30 brushless servo system.

---

[1] See reference [20] for detailed dimensions.

Calibration tests were conducted to characterize the motor. The results are shown in next two figures. Figure 19 contains the calibration data for the motor static torque versus the input voltage to the motor. This data was obtained by restraining the 'yaw' shaft, applying a voltage command to the motor and measuring the output signal from the torque sensor. The overall response is fairly linear but the curve presents a change in slope in the region where the input voltage is between –0.2 and +0.2 Volts. The solid line shown in the plot corresponds to a gain of 21.428 Nm/Volt and represents a least squares fit to the data. On Figure 20 the torque due to motor cogging is shown as a function of the 'yaw' shaft angle, γ. This torque is repeatable but the data has to be recorded again every time the system is taken apart to account for the relative angular displacement between the motor shaft angle and the 'yaw' shaft angle.
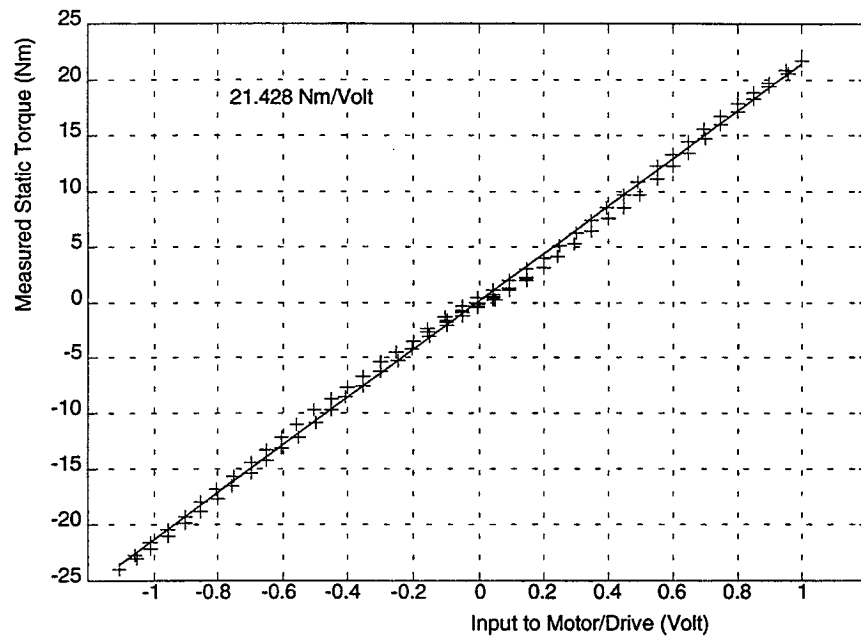

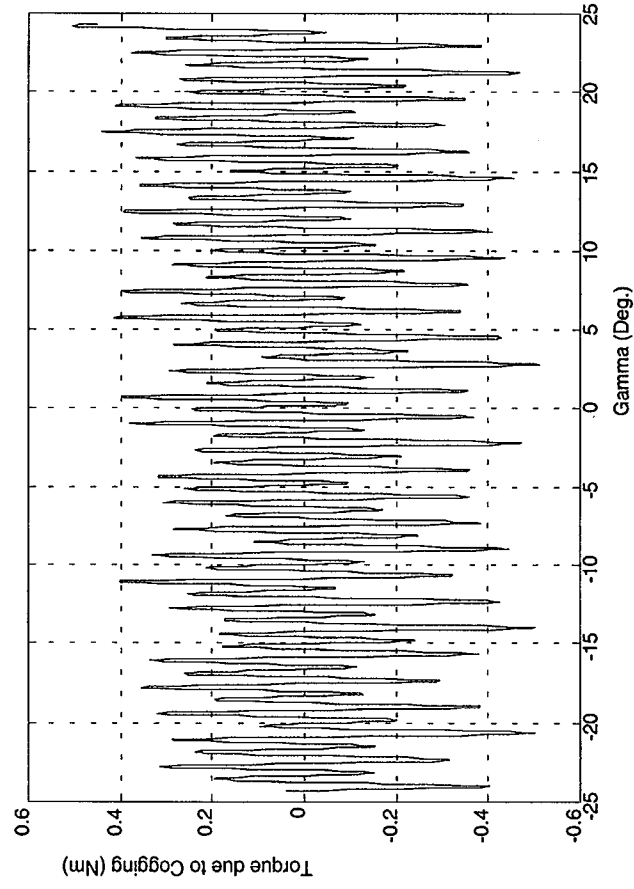Figure 19: Torque motor static calibration.

Figure 20: Torque caused by the cogging in the motor versus the 'yaw' shaft angle.

31

6   Operation During Dynamic Experiments

The operation of the two degrees of freedom apparatus during dynamic experiments requires the use of one computer equipped with A/D and D/A converters to control the active cancellation loop. Inputs to the A/D converter are: the torque from the torque sensor (used as feedback for the inner torque control loop), the 'yaw' shaft angle γ, and the angular acceleration $\ddot{\gamma}$. As described in Section 5.4 the signal from the torque sensor is used as feedback for the inner torque control loop, and the signals for γ and $\ddot{\gamma}$ are used to command the higher level cancellation loop. The output of the D/A converter is a current command sent to the brushless servo system used to apply a torque to the 'yaw' shaft. In general a second computer is used for data acquisition, *e.g.* loads acting on the wind tunnel model, and in the case where active flow control is required a third computer is used to control the servo valves and implement the air injection closed loop control[1]. Currently three IBM-PC compatible micro computers, equipped with A/D - D/A cards[2], are used to perform these tasks. The programs are written in C[3] and make use of real time assembly routines[4] to interface to the A/D - D/A converters.

Use of the apparatus to conduct dynamic experiments is relatively simple but care should taken because the cancellation system can apply large torques to the model supporting structure and the structure could collide with the mechanical stops that limit the motion about the γ-axis causing damage to the system. For this reason safety devices were implemented both mechanically and in the control software. Stops containing cushion material are used to stop the motion before the hard limits are reached. Use of this safety device decreases the range of motion about the γ axis from ± 30 degrees to approximately ± 23 degrees. Also a portable switch, that can be conveniently at hand at all times during the dynamic experiments, is implemented and allows for fast manual turn-off of the input

---

[1] The air injection system is discussed in Section 4.

[2] DT-2821 - Analog and digital I/O board. Data Translation, Inc., 100 Locke Drive, Marlboro, MA 01752-1192 USA.

[3] Turbo C by Borland International, 4585 Scotts Valley Drive, Scotts Valley, CA 95066.

[4] Real time I/O subroutines written by Marc Ullman while a student in the Aeroespace Robotics Laboratory - Stanford University.

to the motor. Safety clauses were added to the software and do not allow more than a certain voltage to be sent as input to the servo system. The software is written in a way that when it is started the system cancels 0% of the external effects, *i.e.* no cancellation occurs, the user can then gradually increase this percentage by using the keyboard, in this way any instabilities or offsets can be identified at a low torque level.

7 Conclusions and Suggested Improvements

A unique experimental apparatus has been designed and built that allows a wind tunnel model two degrees of freedom. The model support system operates in the high angle of attack regime and its degrees of freedom are an approximation to roll and yaw. An active system is used to cancel effects of the apparatus resulting in a system with dynamics dominated by the aerodynamic loads acting on the wind tunnel model.

The apparatus was build to support the active flow control research conducted by the Joint Institute of Aeronautics and Acoustics between Stanford University and NASA Ames Research Center. The system provides a platform to which various wind tunnel models can be mounted and their lateral-directional dynamics (roll-yaw coupling) investigated in a controlled and repeatable environment.

The value and versatility of the apparatus have been demonstrated by its use in the investigation of the dynamics of a delta wing body combination at 45 degrees nominal incidence angle [11,14,15,16]. In those investigations the two degrees of freedom model support system was used as follows: 1) To characterize the flow over the wind tunnel model at 45 degrees angle of attack subjected to transient effects caused by the motion of the model and the application of forebody tangential blowing. 2) To determine the natural motion the system. 3) To demonstrate a closed loop control approach that used forebody tangential blowing as the only actuator to control the roll-yaw motion of the system.

Following are suggestions that the author believes would improve the performance of the existing apparatus:

- *Use of feedforward in the torque control loop.* Currently the torque closed loop control uses feedback logic only. The performance of this control loop can be improved by the use of feedforward in conjunction with feedback. In this way the gain of the feedback loop can probably be reduced and the damping of the closed

loop torque response increased. In addition the non-linearities identified in the motor[1] response can be used to generate a feedforward torque command which would improve the torque loop even further. These are relatively simple to implement improvements requiring mainly software changes.

- *Reduction of the apparatus inertia.* Reducing the inertia of the apparatus about the γ axis would provide a reduction in the required cancellation torque and would increase the first resonance frequency of the structure as a consequence the error in the torque loop would be reduced. Because of the modular characteristic of the design, a roll system which is connected to a 'yaw' system, it is possible to reduce the inertia by modifying the roll-yaw connecting structure only. A more efficient design of this structure would require characterizing the spectra of the loads to which the apparatus is subjected (defined by the unsteady aerodynamics in the operational envelope of the apparatus) and possibly the use of composite materials.

---

[1] Section 5.5.5.

A   Geometry and Mass Properties of the Wind Tunnel Model

In this section the characteristics of four wind tunnel model configurations are presented. The general form of the model is shown in Figure A.1. The model consists of a cone-cylinder fuselage to which wings of different plan-forms as well as vertical fins can be mounted. The different configurations correspond to the possible combinations of delta wings of 60 and 70 degrees sweep angle and the optional use of a vertical fin. The nomenclature used to indicate each of the configurations is given in Table A.1.

Wind Tunnel Model Configurations	
Name	**Description**
N6	60 deg wing sweep angle <u>no</u> vertical fin
T6	60 deg wing sweep angle and vertical fin
N7	70 deg wing sweep angle and <u>no</u> vertical fin
T7	70 deg wing sweep angle and vertical fin

Table A.1: Nomenclature used for the different wind tunnel model configurations.

Figure A.1 includes a cross section of the forebody showing the geometry of the blowing slots. On the cylindrical portion of the forebody the slot has constant width given by $w_{cyl}/D = 0.0087$, where $D = 1.5$ inches is the diameter of the fuselage. On the conical portion of the forebody the slot is tapered, its maximum width is equal to w_{cyl}/D at the junction of the cylindrical and conical sections and its minimum width is $w_{min}/D = 0.0062$ at a station located 0.3 inches from the tip of the conical forebody.

The main characteristics the four wind tunnel model configurations are summarized in Table A.2. The detailed geometry is presented in Figures A.2 through A.5 at the end of this section. Point P, shown in the figures, is defined as the point along the longitudinal axis of the model through which the model rotates in 'yaw', *i.e.* the intersection of the ϕ-axis with the γ-axis.

36

The model is built from Aluminum 6061-T6 and anodized black. The tip of the forebody can be removed and besides the conical tip shown in the drawings a blunt tip consisting of a semi-sphere with a 0.3 inch radius is available. The reference area, S_{ref}, is the area of the wing plan form obtained by extending the leading and trailing edges of the wing. The mean aerodynamic chord shown in the table is defined as

$$\text{MAC} = \frac{1}{S_{ref}} \int_{-b/2}^{b/2} c^2_{(y)} \, dy \qquad (A.1)$$

where b is the wing span and c(y) is the local chord. In Table A.2 the positions of the center of mass and of point P refer to the position along the longitudinal axis of the model and are given as a percentage of the mean aerodynamic chord, MAC.

Characteristics	Model Configuration			
	N6	T6	N7	T7
conical forebody semi-apex angle (deg)	14	14	14	14
wing sweep angle, Λ (deg)	60	60	70	70
wing span, b (in)	7.82	7.82	5.50	5.50
wing plan form area, S_{ref} (in^2)	26.46	26.46	20.68	20.68
wing aspect ratio, $R = b^2/S_{ref}$	2.31	2.31	1.46	1.46
mean aerodynamic chord, MAC (in)	4.51	4.51	5.01	5.01
spanwise location of MAC (in)	1.30	1.30	0.92	0.92
position of center of mass (% of MAC)	18 %	21 %	24 %	27 %
position of point P (% of MAC)	38 %	38 %	44 %	44 %
model plan form area (in^2)	31.54	31.54	25.19	25.19
tunnel blockage at $\alpha_o = 45$ deg	9 %	9 %	7 %	7%
tunnel blockage at $\alpha_o = 90$ deg	12 %	12 %	10 %	10 %

Table A.2: Main characteristics of the various wind tunnel model configurations.

The mass, center of mass and inertia[1] properties for the four configurations are given in Table A.3. Center of mass and inertia are with respect to a reference frame XYZ oriented as shown in Figure A.1. Superscripts CM and P are used to indicate that a quantity is referred to frame XYZ with origin at the center of mass or at point P respectively. In the table, X_{CM}^P, Y_{CM}^P and Z_{CM}^P are the components of the position vector from point P to the center of mass of the model, CM.

Inertia Properties	Model Configuration			
	N6	T6	N7	T7
mass ($\pm$ 0.0001 Kg)	0.6708	0.6913	0.6420	0.6625
X_{CM}^P ($\pm$ 0.03 x 10^{-2} m)	2.27 x 10^{-2}	1.94 x 10^{-2}	2.48 x 10^{-2}	2.13 x 10^{-2}
Y_{CM}^P (m)	0	0	0	0
Z_{CM}^P ($\pm$ 0.05 x 10^{-4} m)	≈ 0	-5.97 x 10^{-4}	≈ 0	-6.22 x 10^{-4}
I_{XX}^{CM} ($\pm$ 0.15 x 10^{-4} Kg m^2)	2.70 x 10^{-4}	3.05 x 10^{-4}	1.76 x 10^{-4}	2.12 x 10^{-4}
I_{YY}^{CM} ($\pm$ 0.05 x 10^{-3} Kg m^2)	2.88 x 10^{-3}	3.25 x 10^{-3}	2.79 x 10^{-3}	3.10 x 10^{-3}
I_{ZZ}^{CM} ($\pm$ 0.02 x 10^{-3} Kg m^2)	3.02 x 10^{-3}	3.19 x 10^{-3}	2.83 x 10^{-3}	3.09 x 10^{-3}
I_{XY}^{CM} (Kg m^2)	0	0	0	0
I_{XZ}^{CM} ($\pm$ 0.1 x 10^{-5} Kg m^2)	≈ 0	-9.0 x 10^{-5}	≈ 0	-9.1 x 10^{-5}
I_{YZ}^{CM} (Kg m^2)	0	0	0	0
I_{XX}^P ($\pm$ 0.15 x 10^{-4} Kg m^2)	2.70 x 10^{-4}	3.06 x 10^{-4}	1.76 x 10^{-4}	2.12 x 10^{-4}
I_{YY}^P ($\pm$ 0.05 x 10^{-3} Kg m^2)	3.24 x 10^{-3}	3.45 x 10^{-3}	3.19 x 10^{-3}	3.40 x 10^{-3}
I_{ZZ}^P ($\pm$ 0.02 x 10^{-3} Kg m^2)	3.34 x 10^{-3}	3.51 x 10^{-3}	3.22 x 10^{-3}	3.39 x 10^{-3}
I_{XY}^P (Kg m^2)	0	0	0	0
I_{XZ}^P ($\pm$ 0.1 x 10^{-5} Kg m^2)	≈ 0	-7.5 x 10^{-5}	≈ 0	-7.5 x 10^{-5}
I_{YZ}^P (Kg m^2)	0	0	0	0

Table A.3: Mass and inertia properties of the various wind tunnel model configurations.

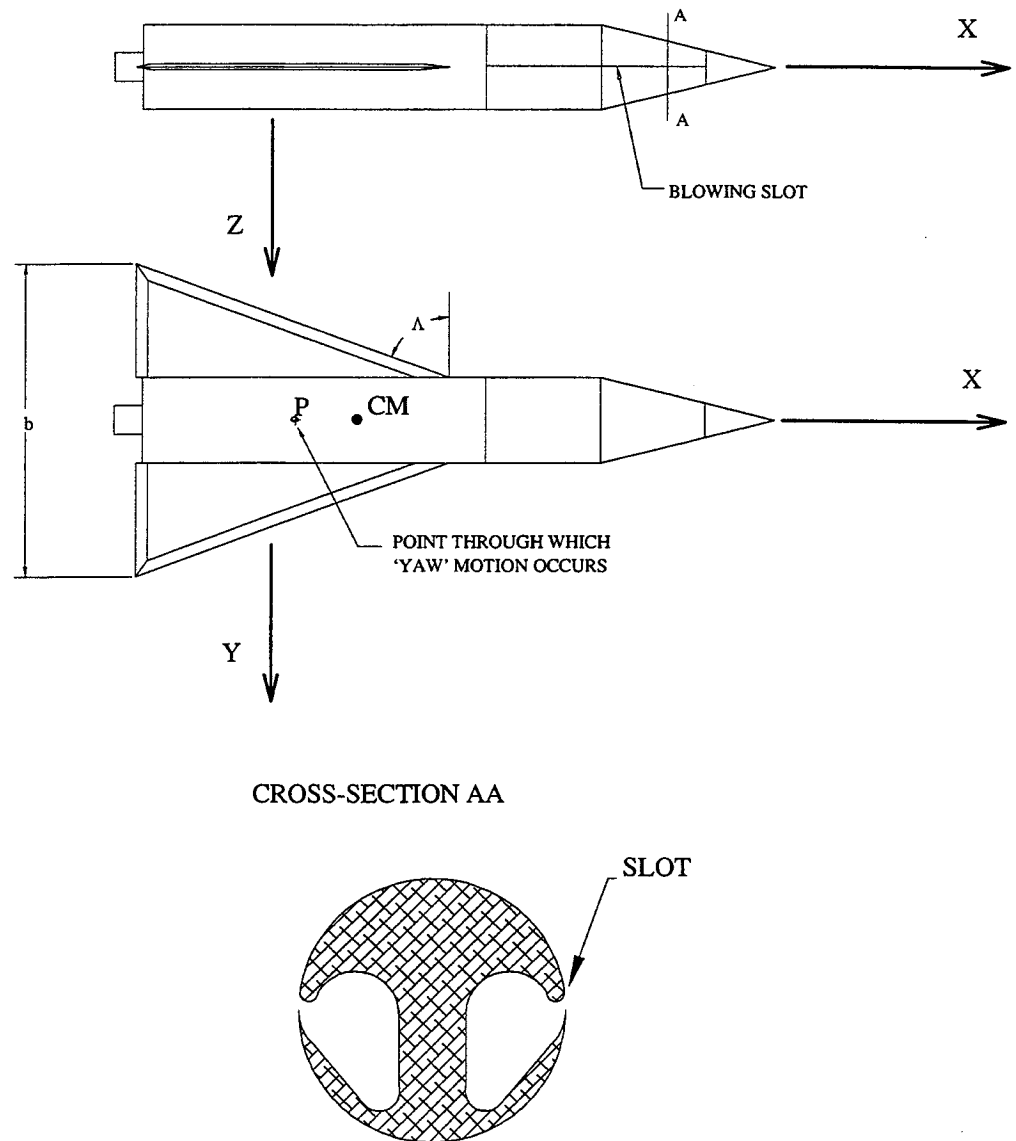[1] Moments of inertia were measured using a torsional pendulum [21].

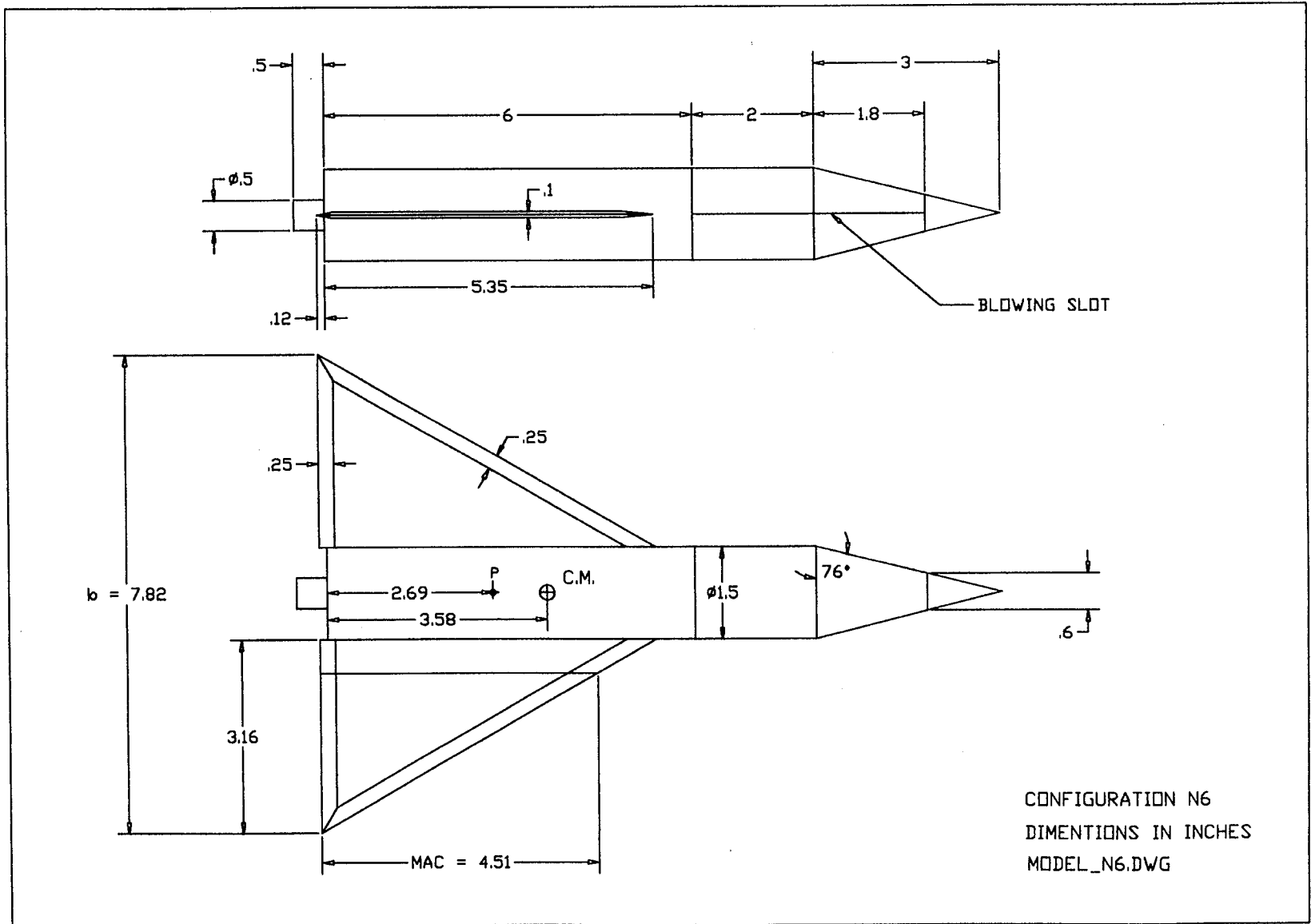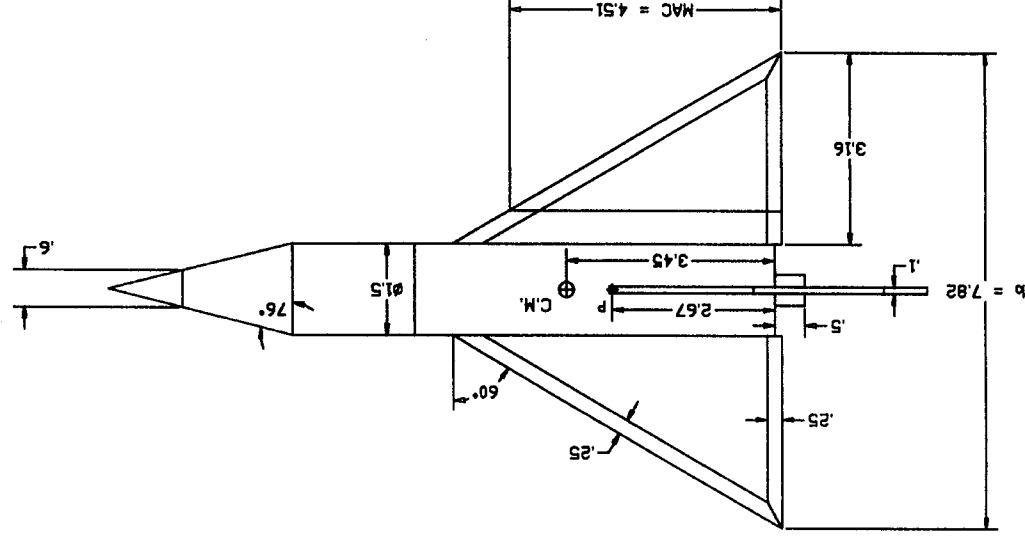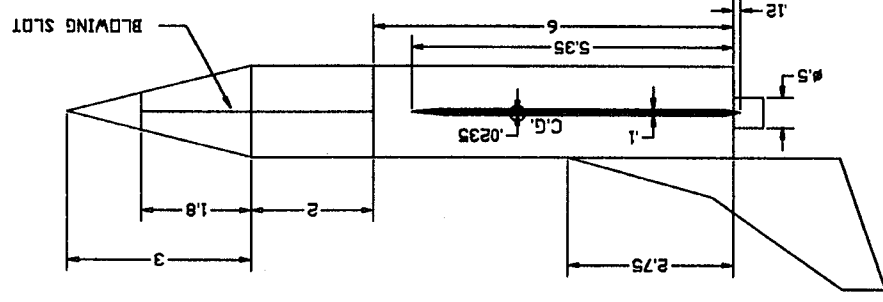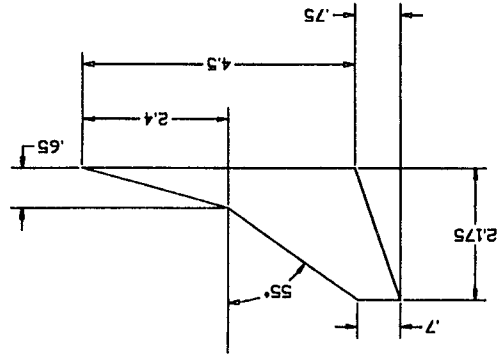Figure A.1: Geometry of the wind tunnel model and detail of blowing slot.

Figure A.2: Detailed geometry for model configuration N6

.5

⌀.5

6

.1

5.35

.12

3

2

1.8

BLOWING SLOT

b = 7.82

.25

.25

3.16

2.69

3.58

P

C.M.

⌀1.5

76°

.6

MAC = 4.51

CONFIGURATION N6
DIMENTIONS IN INCHES
MODEL_N6.DWG

Figure A.3: Detailed geometry for model configuration T6
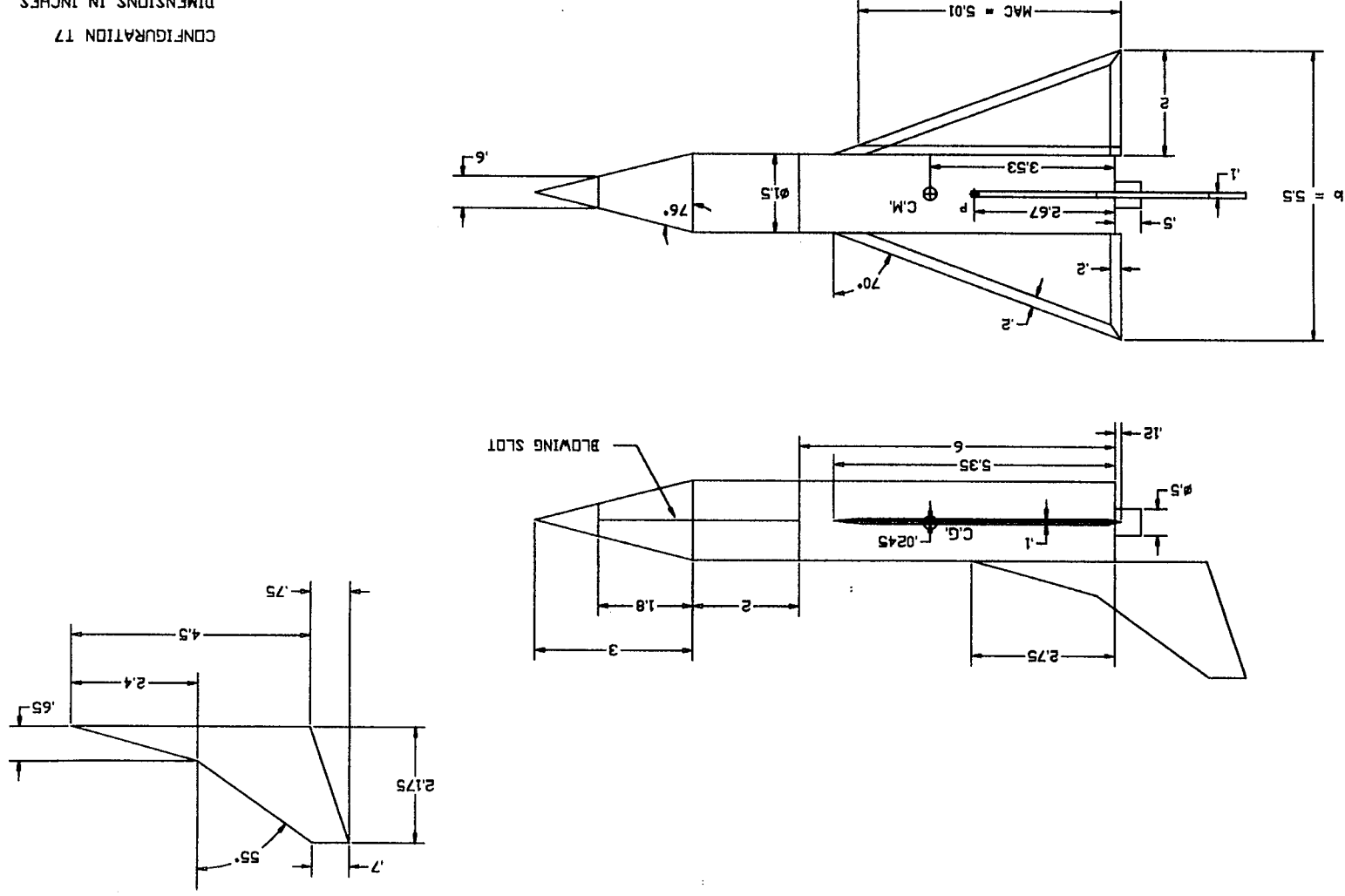
MODEL_N7.DWG
DIMENTIONS IN INCHES
CONFIGURATION N7

MAC = 5.01

2

3.67

Ø1.Ø

C.M.

2.69

b = 5.5

P

2

76°

.6

70°

2

2

BLOWING SLOT

5.35

.12

.1

Ø.5

1.8

2

6

.5

3

Figure A.4: Detailed geometry for model configuration N7

CONFIGURATION T7
DIMENSIONS IN INCHES
MODEL_T7.DWG

Figure A.5: Detailed geometry for model configuration T7

43

B   Servo Valve and Flowmeter

Drawings of the servo valves[1] are shown in Figure B.1. The valve stator and rotor have cut outs and as the angle of the rotor varies so does the area available for the passage of air. A brushless motor is connected to the rotor shaft and a potentiometer is used measure the valve angle. A closed loop control logic is implemented trough an analog circuit to control the rotor angular position [9]. The servo valve, as designed, presents a small leakage and a second rotor, shown in Figure B.2, was designed and built to minimize the leakage.

Two specially designed flowmeters[2] have been built to allow the direct measurement of jet momentum coefficient, C_μ. The design, shown in Figure B.3, uses a miniature pressure transducer[3] to measure the dynamic pressure, p_F^o, at a point at the center line of the flowmeter, from which the jet momentum coefficient is obtained. The dynamic pressure p_F^o is given by:

$$p_F^o = \frac{1}{2}\rho_F^o V_F^{o2} \tag{B.1}$$

where ρ_F^o and V_F^o are respectively the air density and the air speed at the center line of the flowmeter. The mass flow rate, $\dot{m}$, can be written as:

$$\dot{m} = \int_{A_F} \rho_F V_F \, dA = \lambda_F \, \rho_F^o A_F V_F^o \tag{B.2}$$

---

[1] Servo valves designed by Dr. Grant S. Wong [9]. Machined by Mr. Tom Hasler (former Aero/Astro Machine Shop, Stanfor University).
[2] Designed and built by the author.
[3] Kulite Miniature IS® Silicon Diaphragm Pressure Transducer - XCS-093 Series. Kulite Semiconductor Products, Inc. Leonia, NJ 07605.

where A_F is the cross-sectional area of the flowmeter, and λ_F is a constant ($0 < \lambda_F < 1$) that depend on the velocity profile at the flowmeter cross-section where the pressure measurement is taken. λ_F is determined experimentally during the calibration of the flowmeter. From Equations B.1 and B.2 the following expression results for the mass flow rate.

$$\dot{m} = \lambda_F A_F \sqrt{2\, \rho_F^o\, p_F^o} \qquad (B.3)$$

The mass flow rates through the flowmeter and through the exit of the forebody slot are the same:

$$\rho_j A_j V_j = \lambda_F\, \rho_F^o A_F V_F^o \qquad (B.4)$$

where subscript j is used to indicate that a quantity refers to the air jet at the exit of the forebody slot. Recalling the definition of C_μ, from Section 4, and using Equations B.3 and B.4 results:

$$C_\mu \cong 2\lambda_F \frac{A_F^2}{A_j q_\infty S_{ref}} p_d^o \qquad (B.5)$$

where the approximation in the equation is due to the assumption made that the air density inside the flowmeter and at the jet exit are the same. This assumption is reasonable as the flowmeter is built such that $A_F \approx A_j$.

Flowmeter Calibration

The following procedure was used to calibrate the flowmeters: A tube, 0.548 inch internal diameter and 3 feet long, was attached to the exit of the flowmeter and the air velocity profile was determined at the exit of the tube using a miniature Pitot tube mounted to a traversing table. The velocity profiles were numerically integrated to

generate the mass flow rates which were then used in conjunction with the output of the flowmeters to perform the calibration.

Some of the velocity profiles obtained in one of the experiments are shown in Figure B.4, for various mass flow rates. It is assumed that the output of the flowmeter is proportional to the dynamic pressure p_F^o , *i.e.*

$$\vartheta_F = k_v p_F^o \tag{B.6}$$

where ϑ_F is the output of the flowmeter in Volts and k_v is the constant of proportionality. Equations B.3 and B.6 show that the mass flow rate is proportional to the square root of the output of the flowmeter:

$$\dot{m} = \lambda_F A_F \sqrt{\frac{2\rho_F}{k_v}} \sqrt{\vartheta_F} = C_F \sqrt{\vartheta_F} \tag{B.7}$$

In Figure B.5 the mass flow rates obtained trough the integration of the velocity profiles are plotted against the square root of the output of the flowmeter. Also shown is the result obtained with the least squares fit used to determine the constant C_F. This result together with Equations B.3 and B.6 show that the jet momentum coefficient is proportional to the output of the flowmeter.
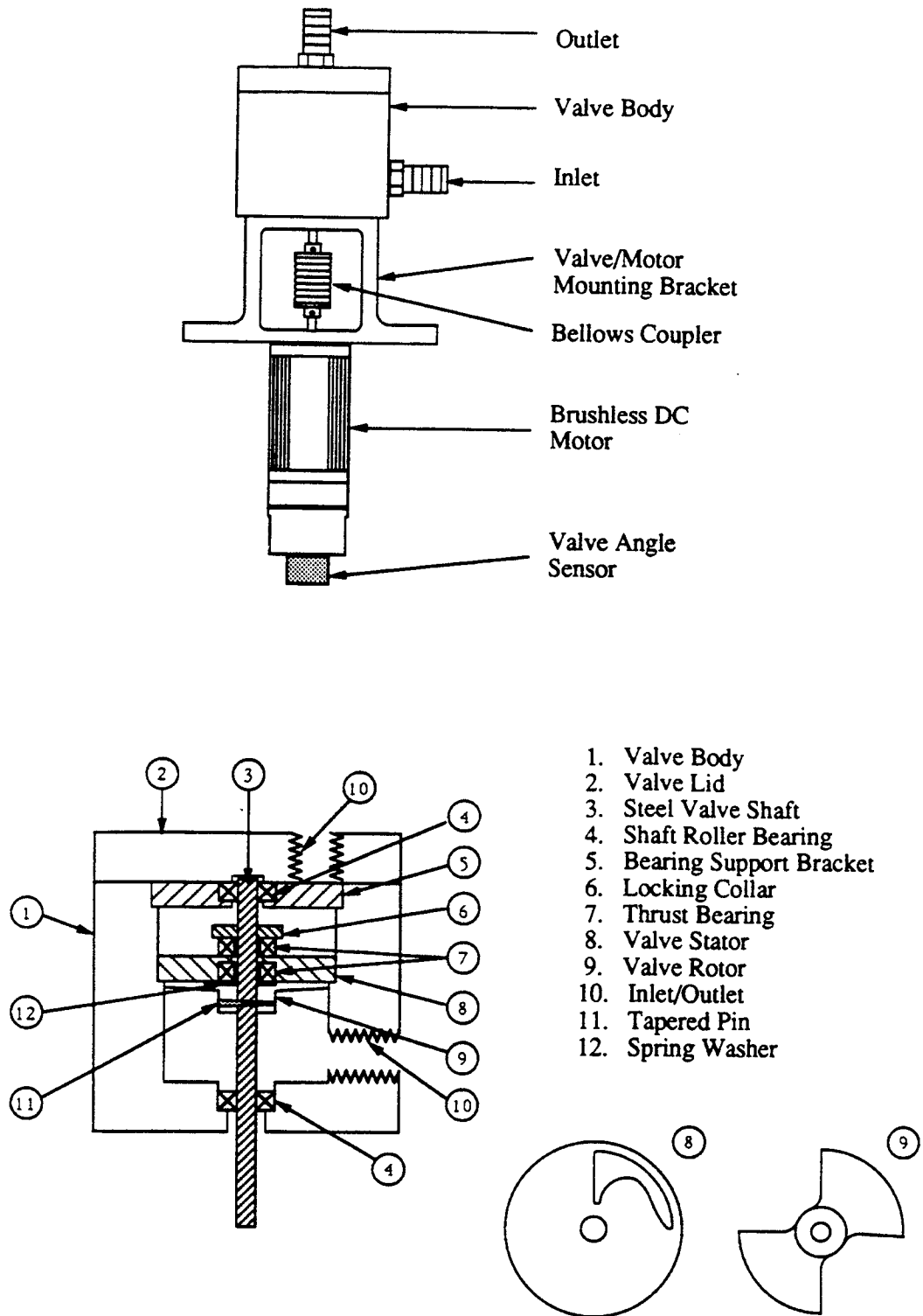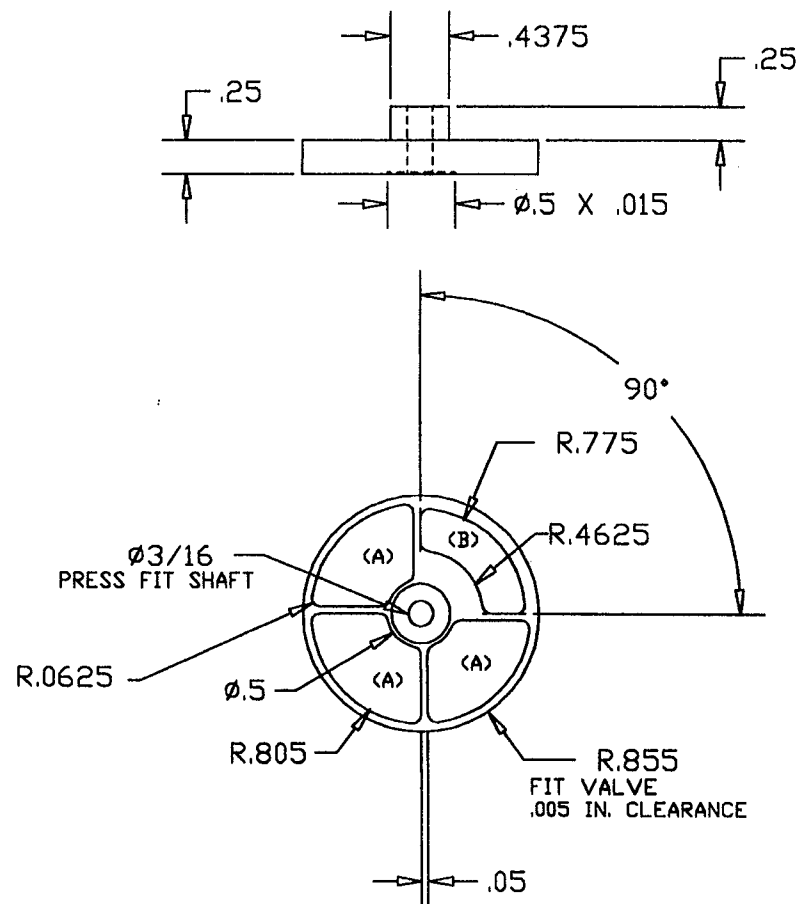
Outlet

Valve Body

Inlet

Valve/Motor
Mounting Bracket

Bellows Coupler

Brushless DC
Motor

Valve Angle
Sensor

1. Valve Body
2. Valve Lid
3. Steel Valve Shaft
4. Shaft Roller Bearing
5. Bearing Support Bracket
6. Locking Collar
7. Thrust Bearing
8. Valve Stator
9. Valve Rotor
10. Inlet/Outlet
11. Tapered Pin
12. Spring Washer

Figure B.1: Servo valve design and configuration. From Wong [9].

.4375

.25

.25

Ø.5 X .015

90°

R.775

R.4625

Ø3/16
PRESS FIT SHAFT

(A)

(B)

(A)

R.0625

Ø.5

(A)

(A)

R.805

R.855
FIT VALVE
.005 IN. CLEARANCE

.05

VALVE_RT.DWG

NOTES:
1. ALUMINUM 6061-T6
2. DIMENSIONS IN INCHES
3. QUANTITY = 2
4. SHOULD FIT VALVE

5. PART IS TO BE MOUNTED ON
A GIVEN SHAFT USING A TAPERED
PIN

(A) .1937 DEEP

(B) THRU

Figure B.2: Alternative design for the servo valve rotor.

48
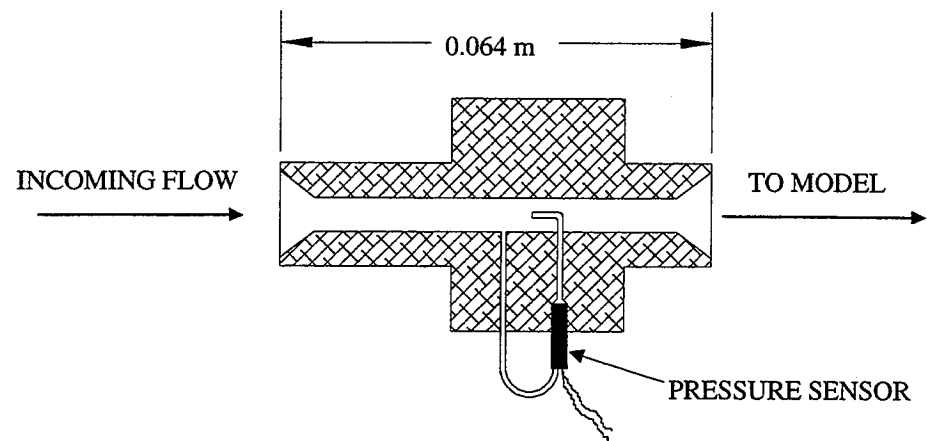
Figure B.3: Flowmeter design and configuration.
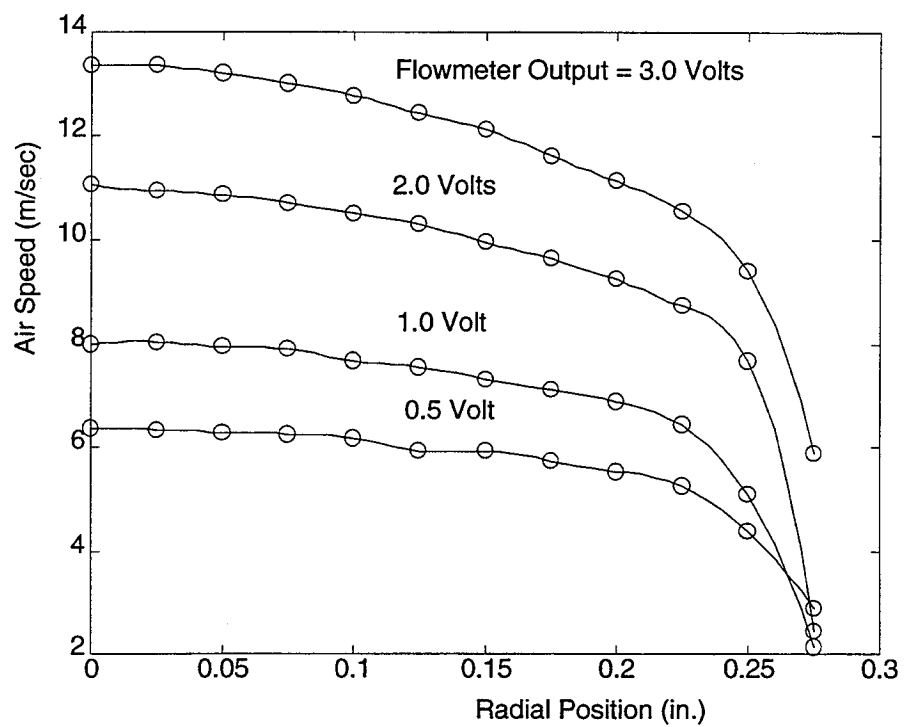
Figure B.4: Velocity profiles at the exit of flowmeter calibration tube.
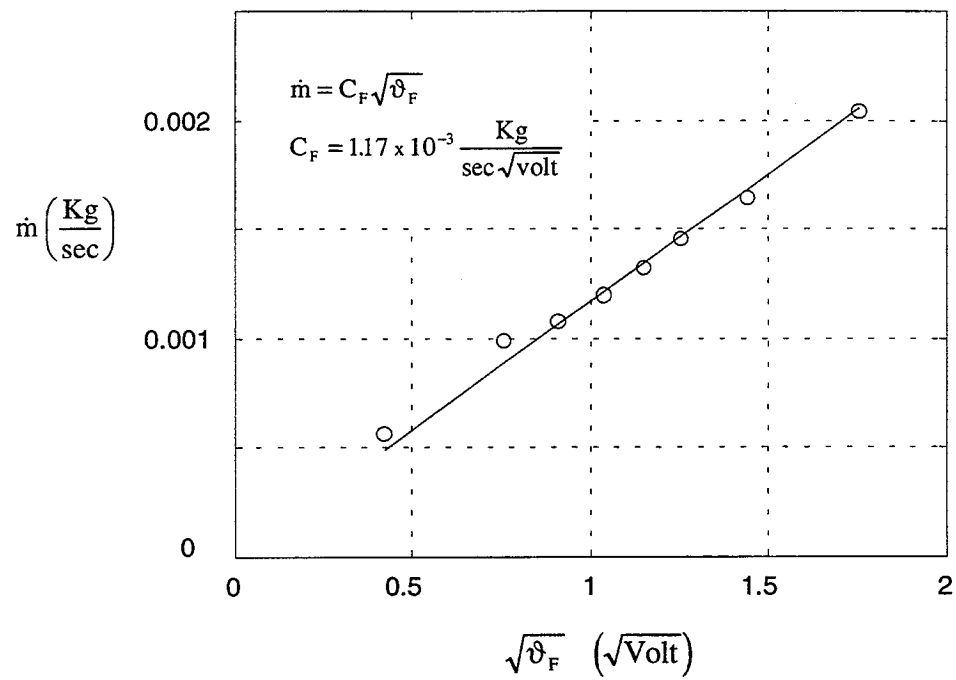
Figure B.5: Flowmeter calibration results.

The plot shows:

$$\dot{m} = C_F \sqrt{\vartheta_F}$$

$$C_F = 1.17 \times 10^{-3} \frac{\text{Kg}}{\text{sec}\sqrt{\text{volt}}}$$

y-axis: $\dot{m}\left(\dfrac{\text{Kg}}{\text{sec}}\right)$

x-axis: $\sqrt{\vartheta_F} \quad \left(\sqrt{\text{Volt}}\right)$

C Model Support System Mechanical Design Drawings

The mechanical design drawings for the components that form the model support system are presented in the following pages. The drawings are divided in three groups according to the sub-system to which they belong. Drawings for the roll sub-system are presented first, followed by drawings for the yaw and for the active cancellation sub-systems. Unless otherwise specified dimensions are in inches and angles in degrees.

It is assumed that the reader who is interested in the detailed design has access to the apparatus and therefore the assembly of the various parts to form the complete system should not pose a problem, nonetheless a few assembly drawings are included to indicate how the various parts fit together.

C.1 Roll Sub-system

The mechanical components of the roll sub-system are identified on the assembly drawing presented in Figure C.1. A wind tunnel model is shown in the drawing to indicate how it is mounted to the roll system.

The roll shaft is mounted to the roll support structure through precision bearings[1]. and held in place by two collars as shown in the figure. Part ENDPLT2A, the 6-component force-torque sensor, and part ENDPLT2B are used to connect the wind tunnel model to the roll shaft. Part ROLLEND connects the shaft of the potentiometer to the roll shaft.

The air supply tubing are not shown in the drawing. The tubing are routed from the yaw sub-system to the interior of the roll shaft through part ROLLEND, they emerge at the other end of the roll shaft at the section where the shaft diameter changes from 1 to 0.5 inches and are connected to special ports at the rear end of the model. Part ROLLOCK is used to constrain the motion of the roll shaft at a desired roll angle during static experiments.

It is possible to mount a motor[2] to the roll system for the purposes of driving the roll motion or canceling external effects such as the friction from the bearings and potentiometer and disturbances from the air supply tubing. The detailed drawings for parts MTRFXA and MTRFXB which are used to mount the motor to the roll system are included.

---

[1] Kaydon KAA10CL4 ball bearing. Kaydon Corporation, Muskegon, Michigan 49443 USA.
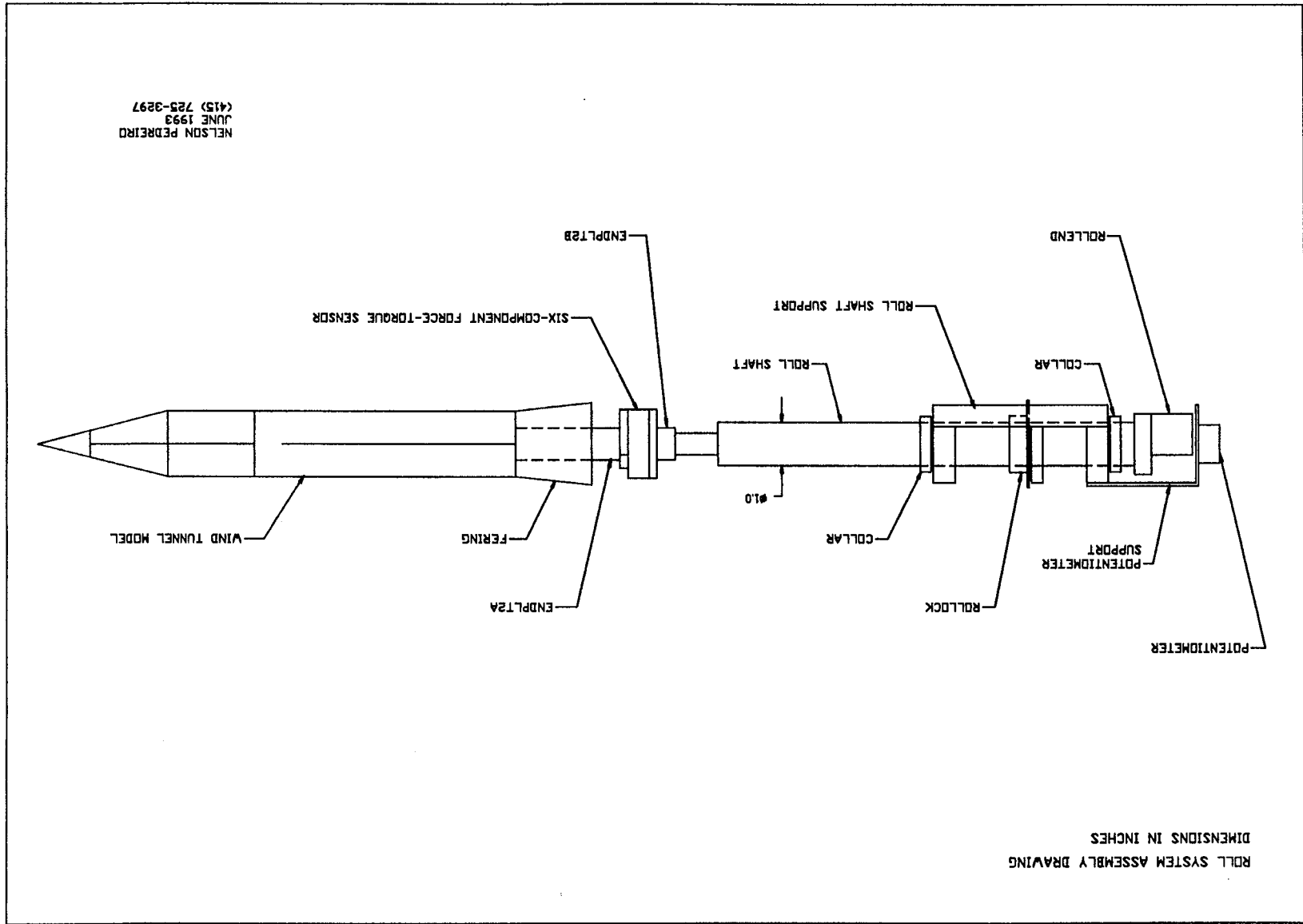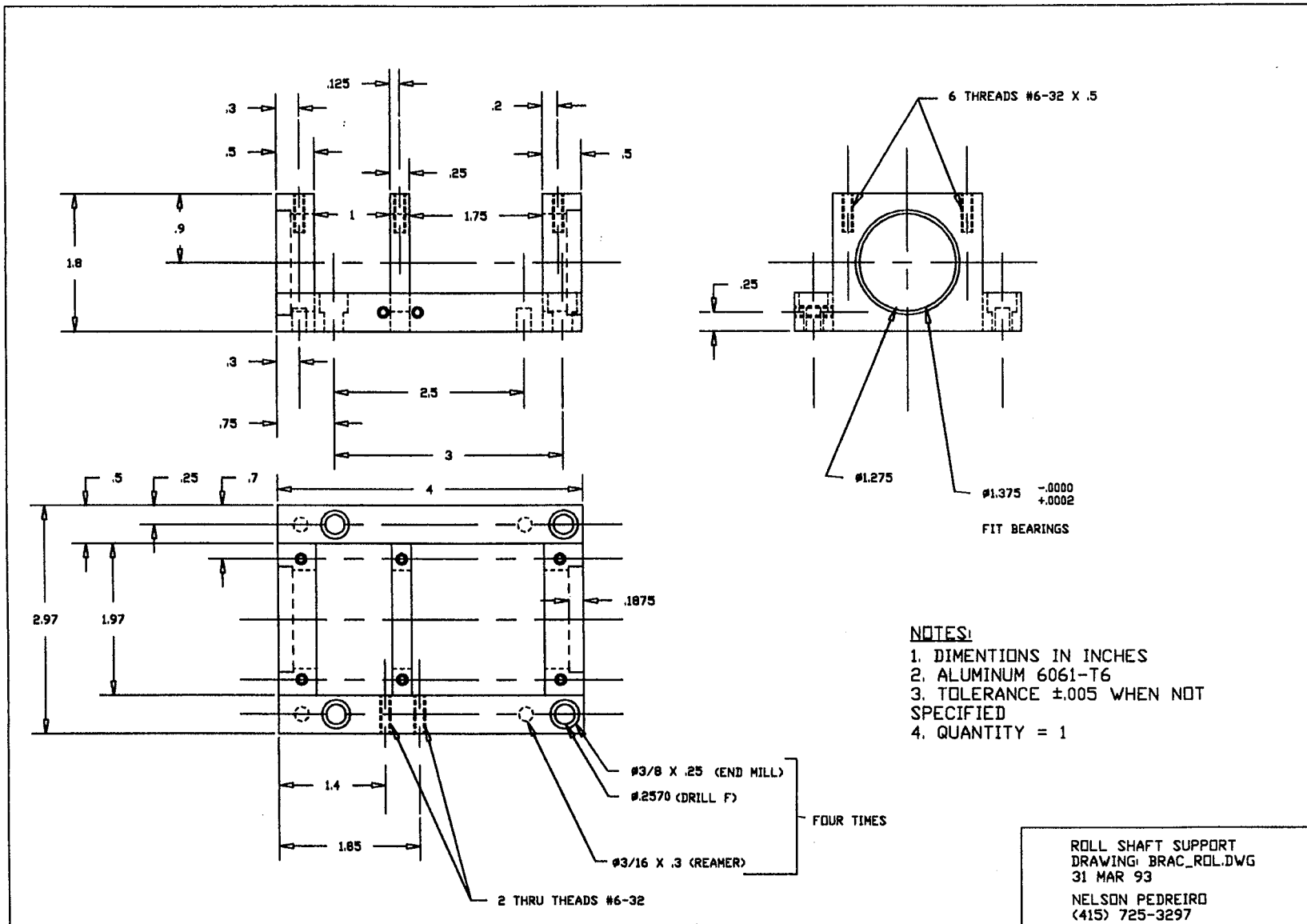[2] Elcom 3111 WDG#4. Pittman Motors, Harleysville, PA 19438-003 USA.
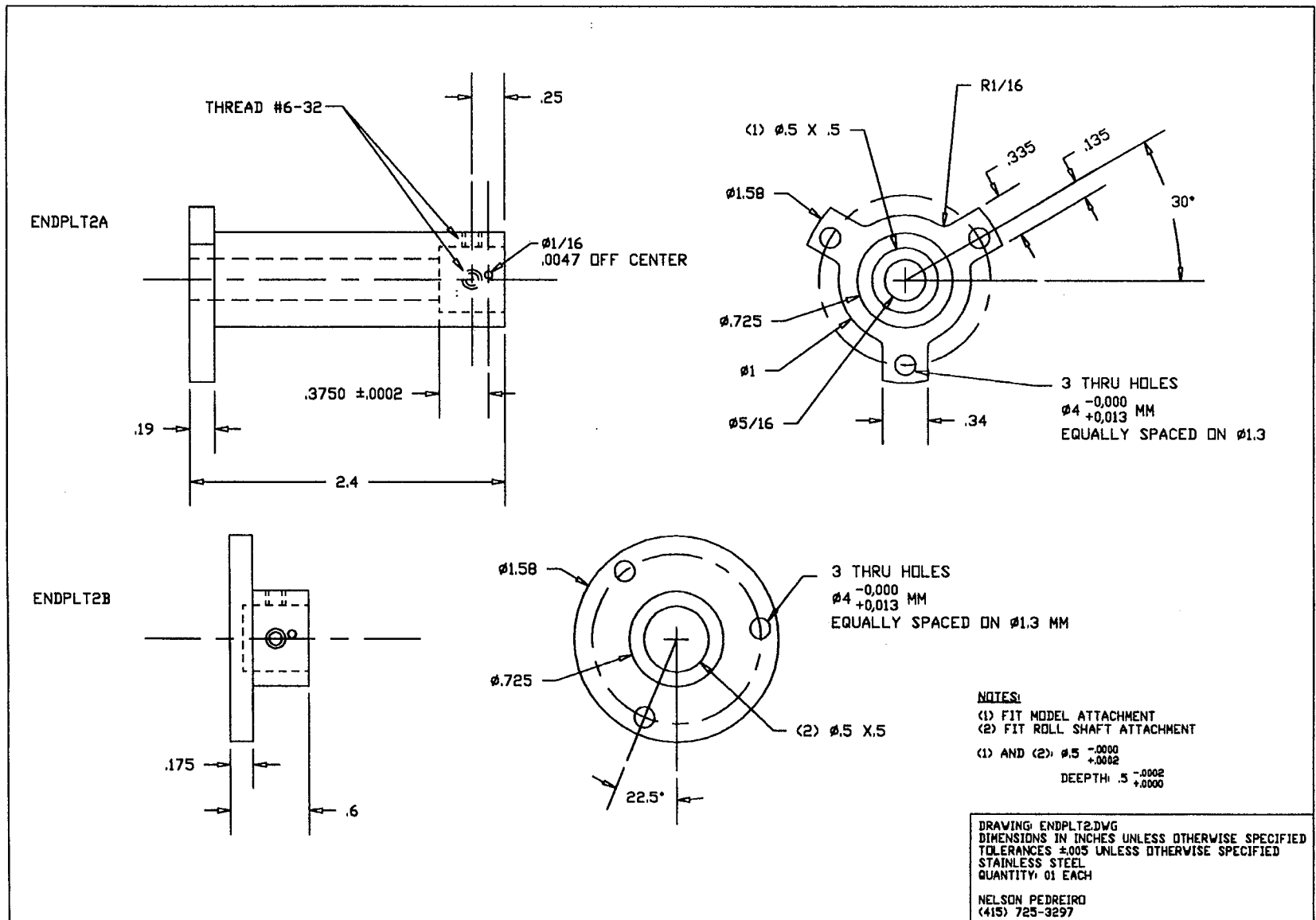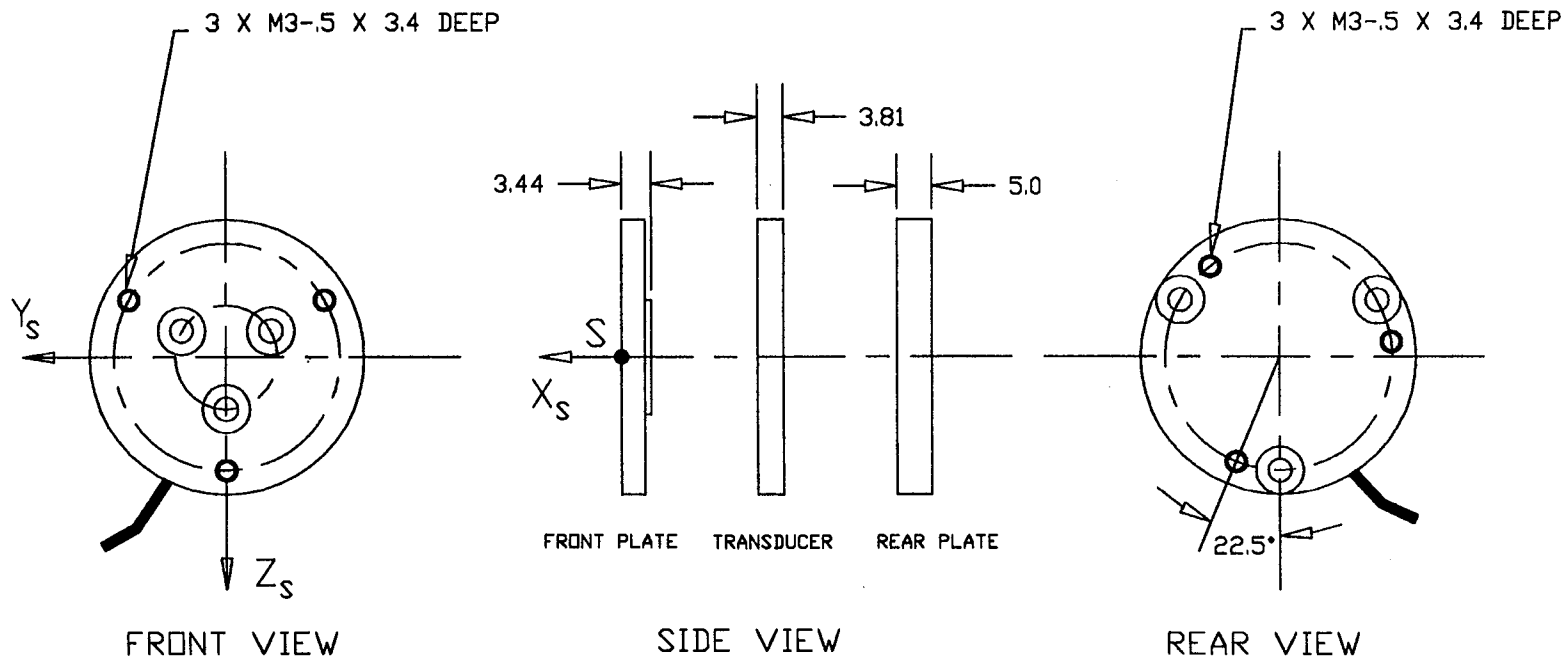
Figure C.1: Roll system assembly drawing.

54

6 THREADS #6-32 X .5

.125

.3

.5

.2

.5

.25

1

1.75

.9

1.8

.25

.3

2.5

.75

3

.5 .25 .7

4

2.97 1.97

.1875

ø1.275

ø1.375 −.0000 +.0002

FIT BEARINGS

NOTES:
1. DIMENTIONS IN INCHES
2. ALUMINUM 6061-T6
3. TOLERANCE ±.005 WHEN NOT SPECIFIED
4. QUANTITY = 1

ø3/8 X .25 (END MILL)

ø.2570 (DRILL F)

FOUR TIMES

1.4

1.85

ø3/16 X .3 (REAMER)

2 THRU THEADS #6-32

ROLL SHAFT SUPPORT
DRAWING: BRAC_ROL.DWG
31 MAR 93

NELSON PEDREIRO
(415) 725-3297

10.2

.5

.2

.4

2.1

1.9

1/16

.8

1

−.0000
+.0002

1

.5

FIT SENSOR

10 FLATS .25 IN LONG
.01 IN DEEP

HOLE AND FLATS
TO FIT SENSOR

2 THRU HOLES
⌀3/32

30°

20°

40°

⌀1

⌀.905

⌀.68

8 THRU HOLES ⌀3/16
EQUALY SPACED AT 40°

CONNECT WITH ⌀1/8

ROLL SHAFT

NOTES:
1. DIMENTIONS IN INCHES
2. STAINLESS STEEL − 304
3. TOLERANCE ±.005 WHEN NOT SPECIFIED
4. QUANTITY = 1

SHAFT TOLERANCES FOR FITTING THE BEARINGS ARE: −.0000
+.0002

ENDPLT2A

THREAD #6-32

.25

Ø1/16
.0047 OFF CENTER

.3750 ±.0002

.19

2.4

R1/16

(1) Ø.5 X .5

.335

.135

30°

Ø1.58

Ø.725

Ø1

Ø5/16

.34

3 THRU HOLES
Ø4 $^{-0,000}_{+0,013}$ MM
EQUALLY SPACED ON Ø1.3

ENDPLT2B

.175

.6

Ø1.58

3 THRU HOLES
Ø4 $^{-0,000}_{+0,013}$ MM
EQUALLY SPACED ON Ø1.3 MM

Ø.725

(2) Ø.5 X.5

22.5°

NOTES:
(1) FIT MODEL ATTACHMENT
(2) FIT ROLL SHAFT ATTACHMENT

(1) AND (2): Ø.5 $^{-.0000}_{+.0002}$

DEEPTH: .5 $^{-.0002}_{+.0000}$

DRAWING: ENDPLT2.DWG
DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED
TOLERANCES ±.005 UNLESS OTHERWISE SPECIFIED
STAINLESS STEEL
QUANTITY: 01 EACH

NELSON PEDREIRO
(415) 725-3297

SIX-COMPONENT FORCE-TORQUE SENSOR MANUFACTURED BY ASSURANCE TECHNOLOGIES, INC.
MODEL - MINI 90N/4.2Nm

3 X M3-.5 X 3.4 DEEP

3 X M3-.5 X 3.4 DEEP

3.81

3.44

5.0

Y_S

X_S

Z_S

FRONT PLATE   TRANSDUCER   REAR PLATE

22.5°

FRONT VIEW

SIDE VIEW

REAR VIEW

SENSOR ASSEMBLED WITH
INTERFACE PLATES

⌀40

12.25

S

X_S

.2188

.4874

2 THRU THEADS
#8-32

.1

8 × Ø3/16

.2688

.2875

.1

.2875

.2875

1.4

.2

1.2

1.4

Ø1

Ø1.4

.1

Ø.25

1

.5

.6
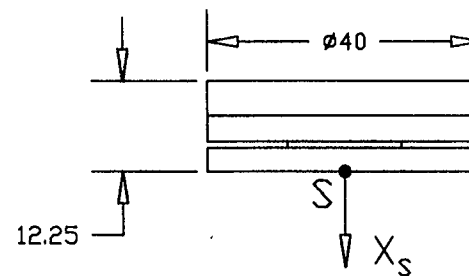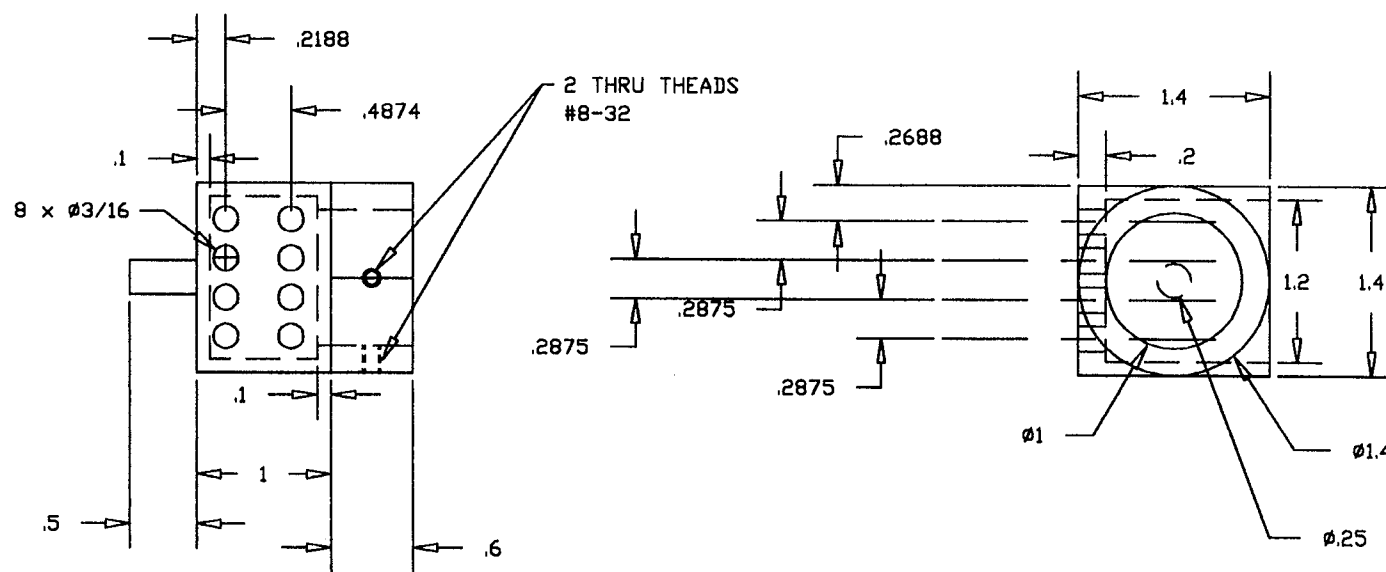
NOTES:
1. DIMENSIONS IN INCHES
2. ALUMINUM 6061-T6
3. TOLERANCE ±.005 UNLESS
OTHERWISE SPECIFIED
4. QUANTITY: 1

NOTES:
1. DIMENTIONS IN INCHES
2. ALUMINUM – 6061-T6
3. TOLERANCE ±.005
4. QUANTITY =1

MTRFXA
DRAWING: MOTRFIX.DWG

Ø1/8 X .3

.25

1.65

1.375

.35

.2

.8

.3

1.4

.063

.9056
(23 MM)

.4528
(11.5 MM)

4 THRU HOLES Ø1/8

Ø1/4

Ø5/8 X .063

.4528
(11.5 MM)

.6

.875

.25

.55

.85

2.62

THREAD
6-32

A

Ø.14

.25

A

.1

THREAD 4-40

.3

.3

2.5

CROSS-SECTION AA

.3

.25
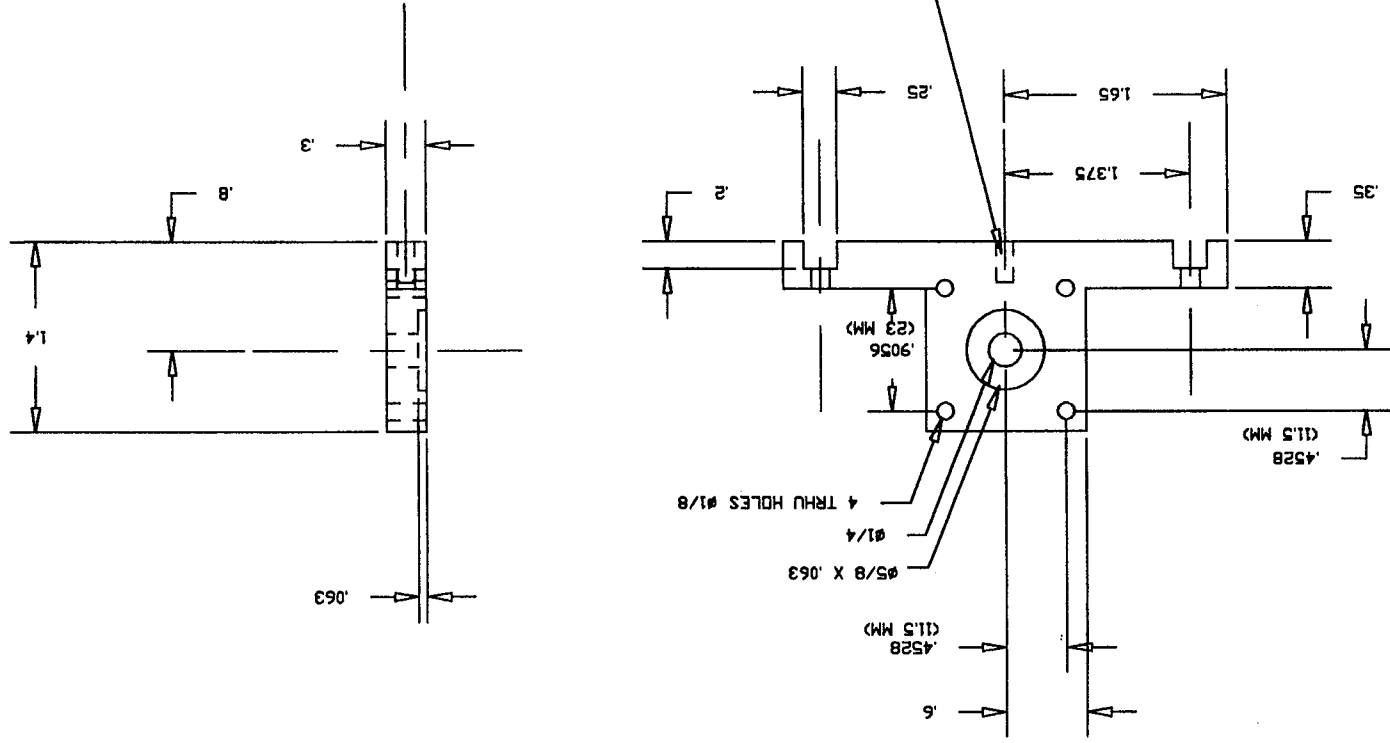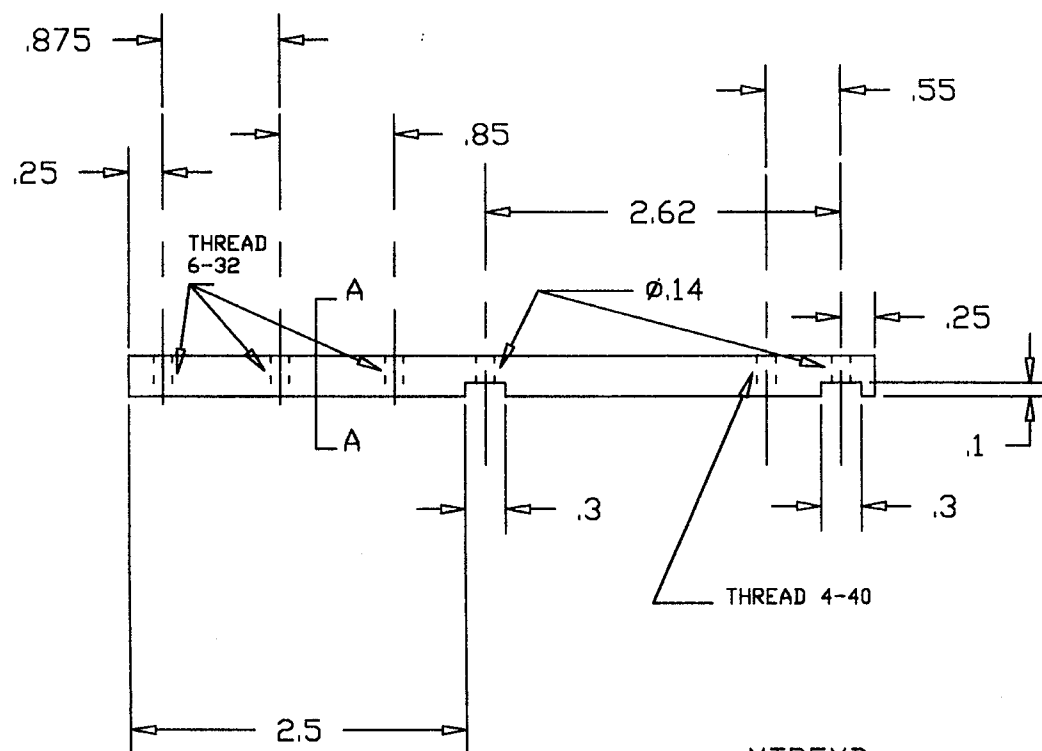
MTRFXB

DRAWING: ROLL3.DWG

NOTES:
1. DIMENTIONS IN INCHES
2. ALUMINUM - 6061-T6
3. TOLERANCE ±.005 IN. IF NOT SPECIFIED
4. QUANTITY = 2

61

C.2   Yaw Sub-system

Assembly drawings are presented in Figure C.2 for the main components of the yaw subsystem. Parts SPS1 and SPS2 are welded to a 20.2 inch long aluminum tube with 3 inch external diameter and 1/16 inch wall thickness, the resulting part is used to connect the roll sub-system to the yaw shaft trough part R. Rotation about the γ or 'yaw' axis is obtained by mounting the yaw shaft to a co-axial aluminum structure, the yaw shaft support, through the use of bearings[1]. The yaw shaft support is mounted to part F which with parts C, CD, E, and D form an assembly that is mounted to the test section supporting structure. The test section is bolted to the two L- beams shown in the figure, it has a cut on the bottom wall to allow the entrance of the roll shaft in the test section.

Parts C can slide on the four parallel stainless steel ground stock to allow adjustment of the position of the whole system along the longitudinal axis of the test section. The yaw shaft support, part G, can be fixed to part F at any position within a certain range to allow for the adjustment of the distance between the wind tunnel model and the bottom wall of the test section. Parts E are mounted to parts D through the use of shoulder screws and allow for adjustment of the incidence angle in the range from 35 to 55 degrees.

---

[1] BERG Ball Bearings - #B1-21 - UNSHIELDED.
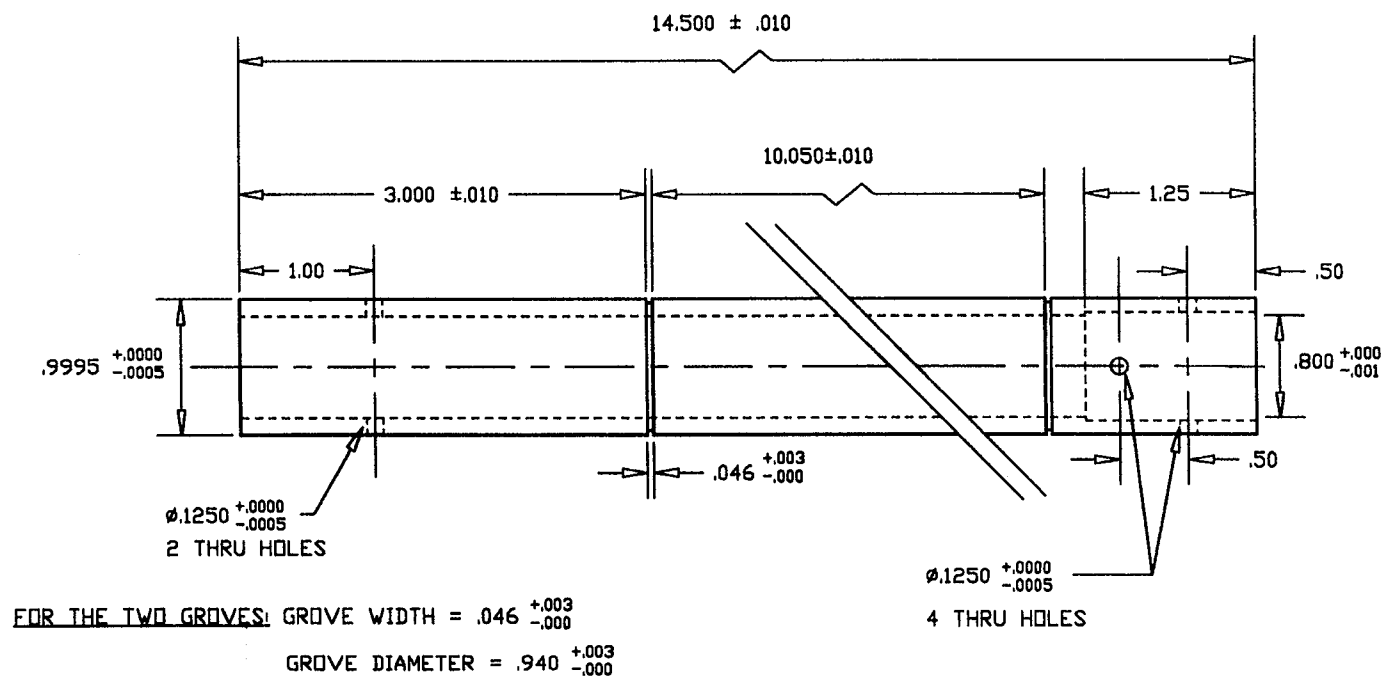
Figure C.2: Yaw system assembly drawing.

63

FEATURE A: FIT ROLL SHAFT
SUPPORT WITH DOWEL PINS
4 X Ø3/16 X .3
(REAMER)

4 THREADS
#1/4-20 X .5

3

2.5

.25

.25

.45

PART: SPS1
DRAWING SPS1.DWG
TOLERANCES ±.005 EXCEPT FOR
FEATURE A THAT NEEDS TO FIT ROLL
SHAFT SUPPORT (BRAC_ROL.DWG)
ALUMINUM 6061-T6
QUANTITY = 01

Ø2.875

Ø2.625

3

3

3.25

2

64
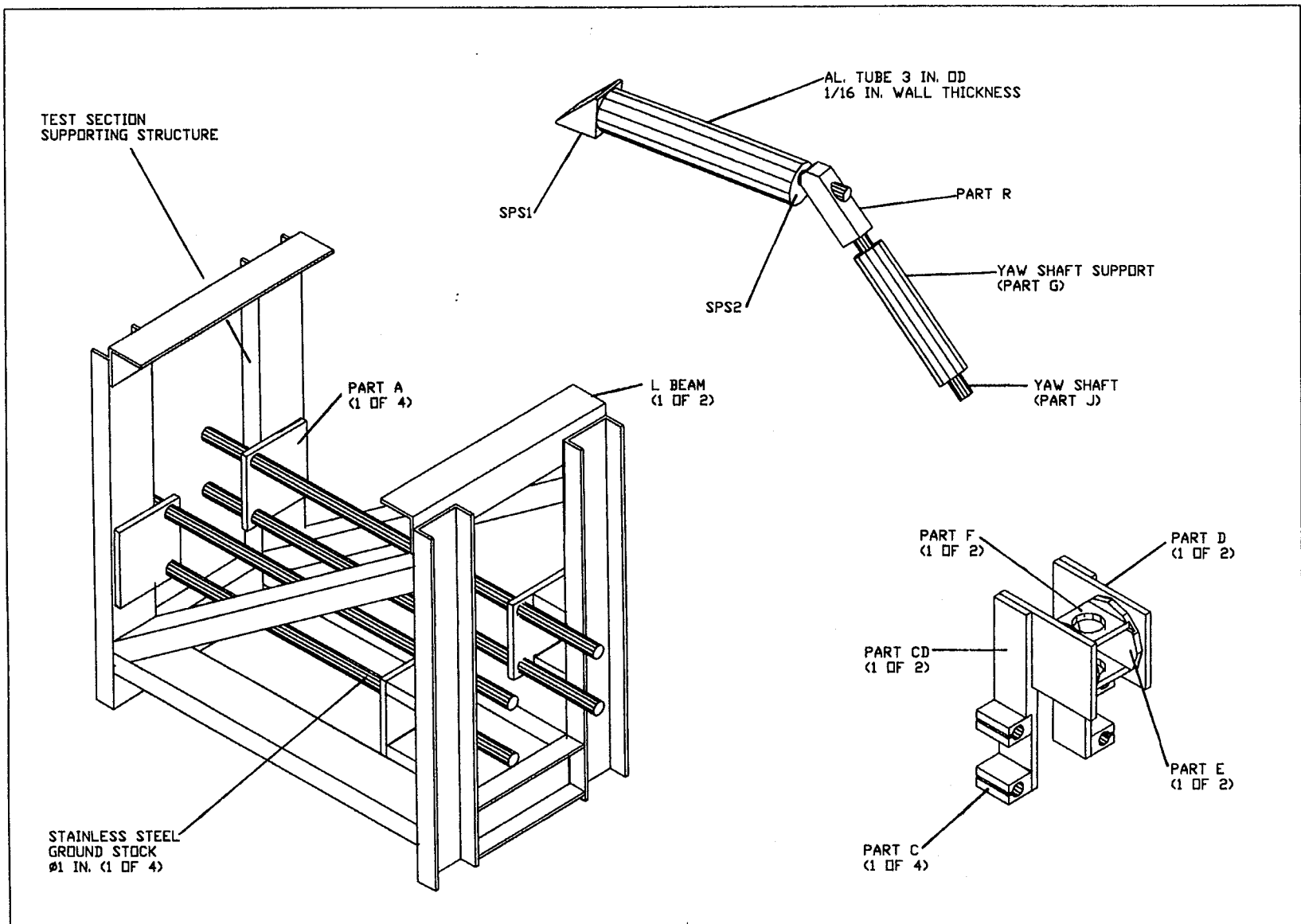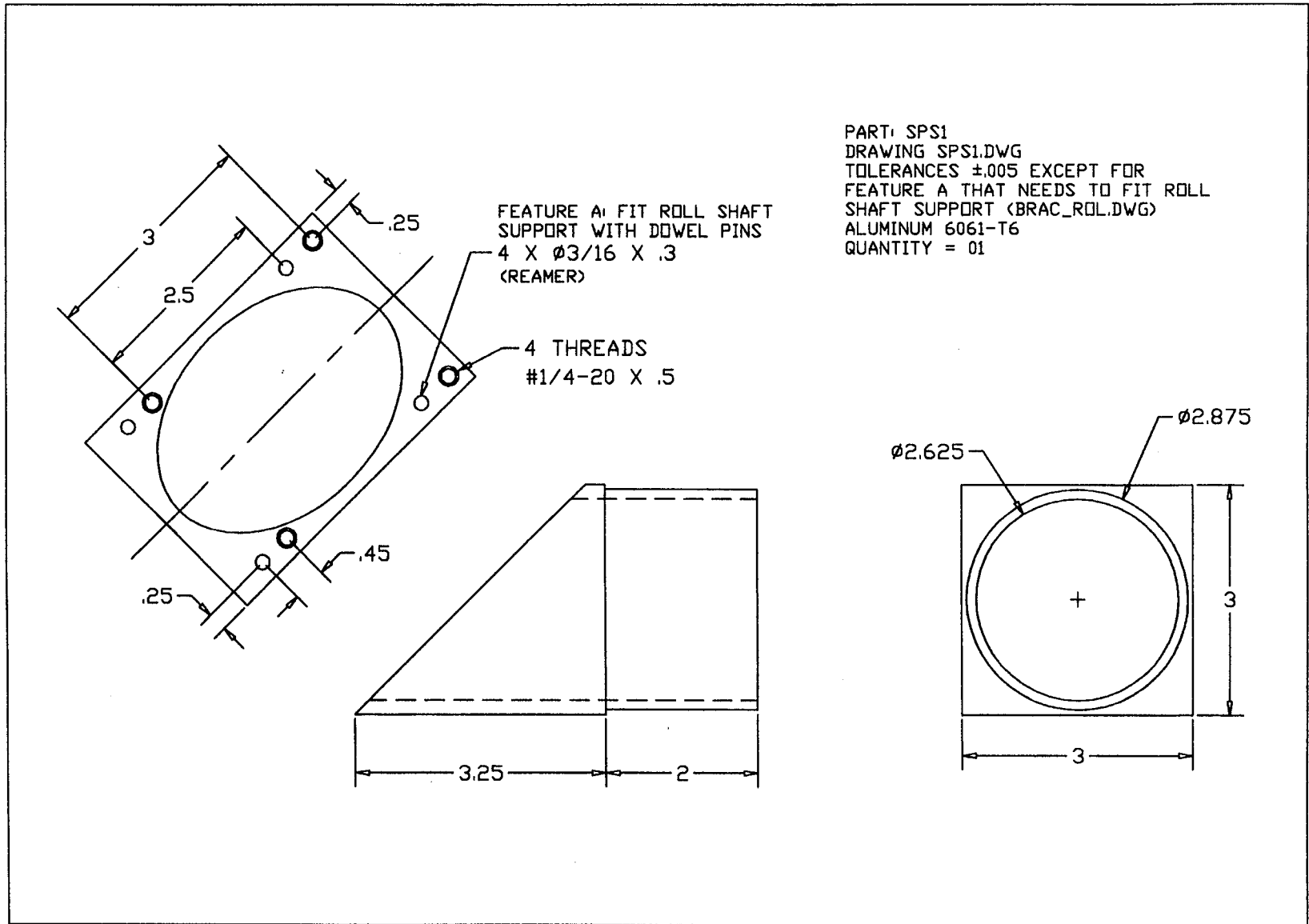
PART: SPS2
DRAWING SPS2.DWG
TOLERANCES ±.005 IF NOT SPECIFIED

ALUMINUM 6061-T6
QUANTITY = 01
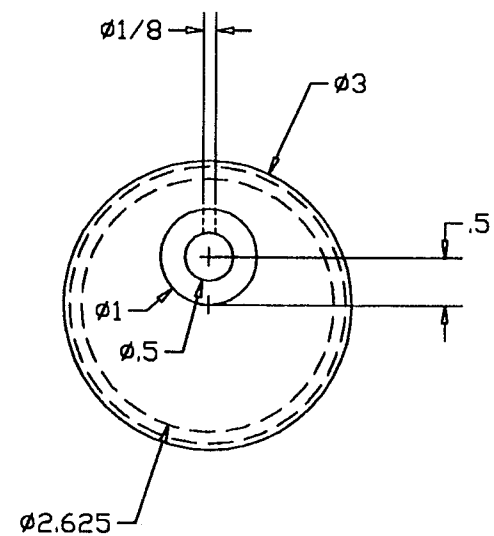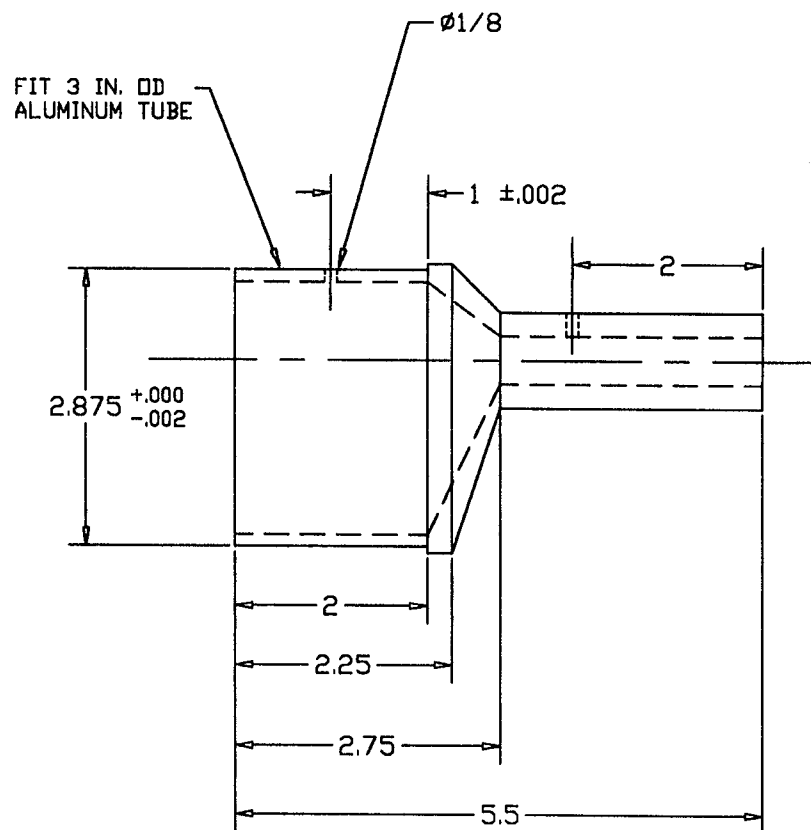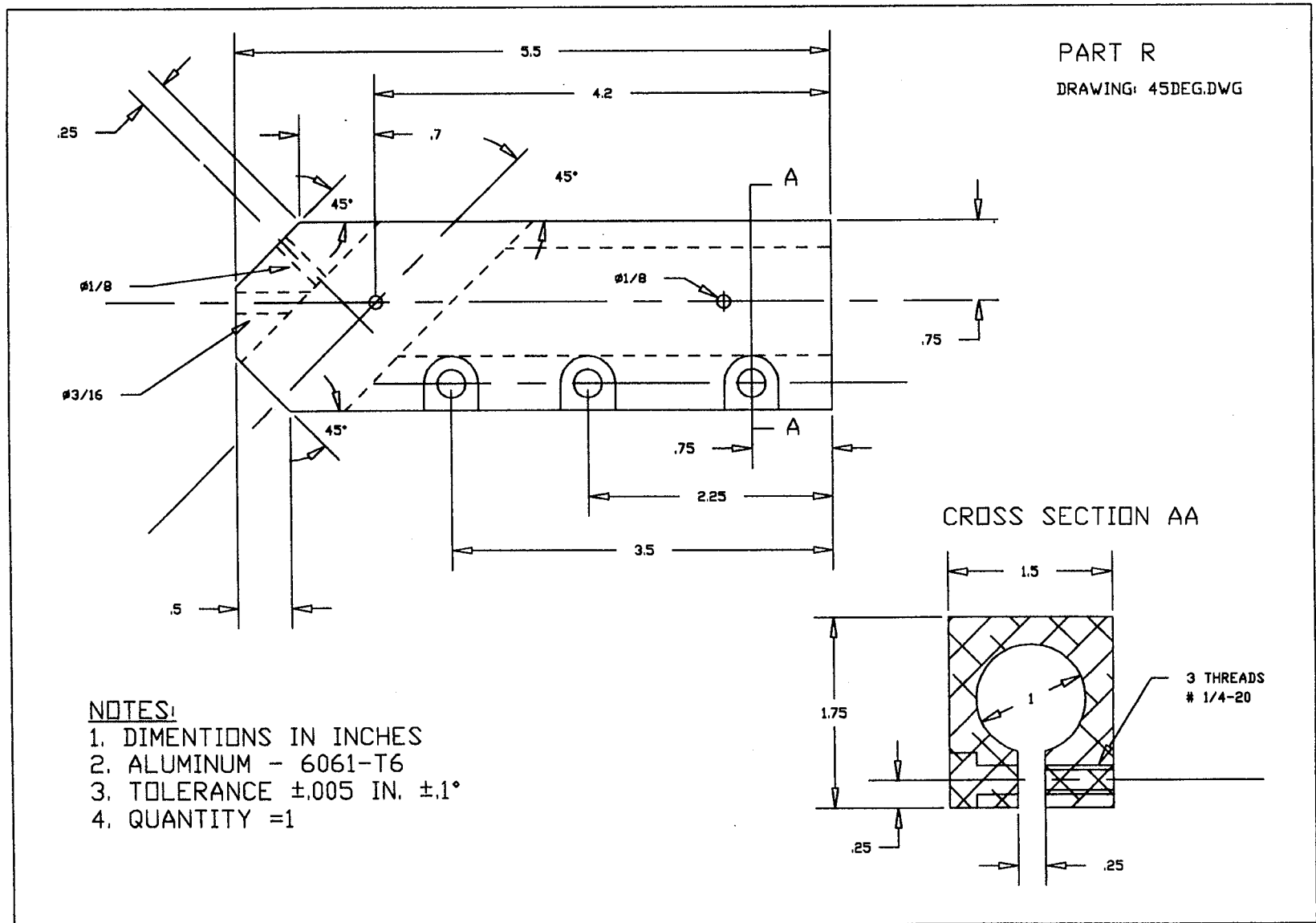
Ø1/8

FIT 3 IN. OD
ALUMINUM TUBE

1 ±.002

2

2.875 $^{+.000}_{-.002}$

2

2.25

2.75

5.5

Ø1/8

Ø3

.5

Ø1

Ø.5

Ø2.625

PART R

DRAWING: 45DEG.DWG

5.5

4.2

.7

45°

A

.25

45°

Ø1/8

Ø1/8

.75

Ø3/16

45°

.75

A

2.25

3.5

CROSS SECTION AA

.5

1.5

1.75

1

3 THREADS
1/4-20

NOTES:
1. DIMENTIONS IN INCHES
2. ALUMINUM - 6061-T6
3. TOLERANCE ±.005 IN. ±.1°
4. QUANTITY =1

.25

.25

66

NOTES:
1. DIMENTIONS IN INCHES
2. STAINLESS STEEL TUBE – CENTERLESS GROUND
3. WALL THICKNESS 1/8 IN.
4. QUANTITY 1
5. SEE DRAWING J02 FOR DETAILS
   OF PART BETWEEN GROVES

14.500 ± .010

10.050±.010

3.000 ±.010

1.25

1.00

.50

.9995 $^{+.0000}_{-.0005}$

.800 $^{+.000}_{-.001}$

.046 $^{+.003}_{-.000}$

.50

Ø.1250 $^{+.0000}_{-.0005}$
2 THRU HOLES

Ø.1250 $^{+.0000}_{-.0005}$
4 THRU HOLES

FOR THE TWO GROVES: GROVE WIDTH = .046 $^{+.003}_{-.000}$

GROVE DIAMETER = .940 $^{+.003}_{-.000}$

67

PART J
J01
SCALE 1:1

NOTES:
1. DIMENTIONS IN INCHES
2. STAINLESS STEEL TUBE – CENTERLESS GROUND
3. WALL THICKNESS 1/8 IN.
4. QUANTITY 1

OVERALL VIEW

14.50

8.00

7.00

6.00

5.00

#6-32 – UNC
8 THRU THREADS
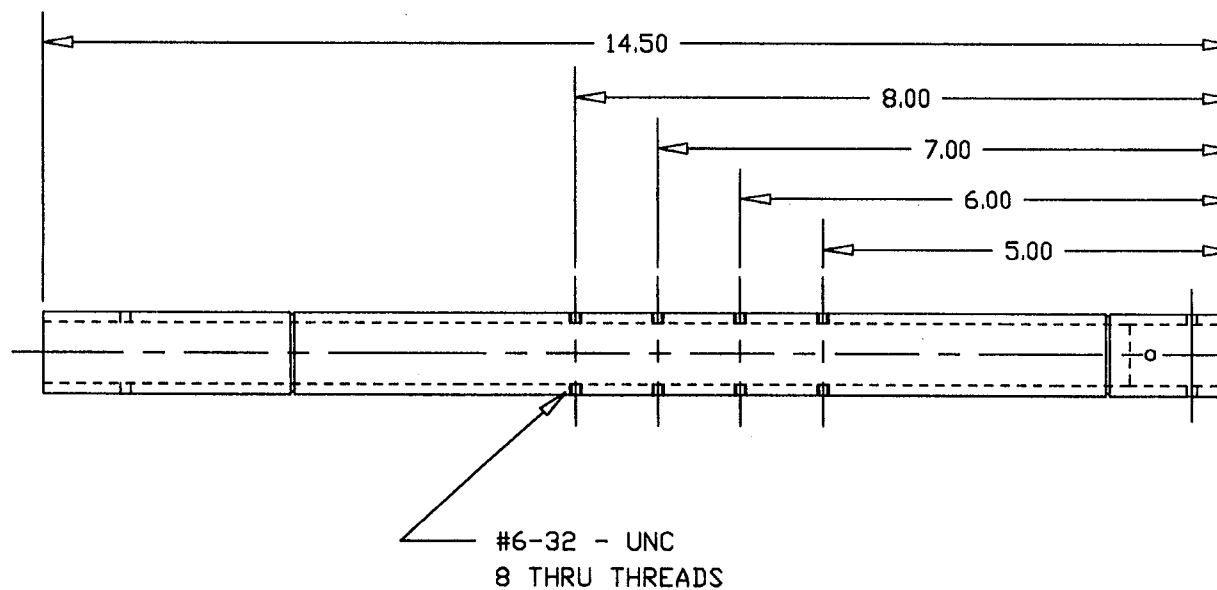
PART J
J02
SCALE 1:2

THIS SHAFT HAS ∅1/8 HOLES AS SHOWN
HOLES WITH ∅1/4 AND ∅5/16 FOR DOWEL PINS ARE
TO BE ADDED AS SHOWN

∅.3125   ∅.3125   ∅.2500   ∅.3125

.925   .6750 ±.0002   .4187   .5563 ±.0002

MODIFIED AS OF 05JAN94	PART J
DRAWING: YAWSYS6M	DIMENSIONS IN INCHES
NELSON PEDREIRO (415) 725-3297	SCALE 1:1

#10-32 - UNF
4 TRHU THREADS

$\phi 2.250 ^{+.000}_{-.005}$

6.50

5.50

4.50

3.50

.75

A

$\phi 2.0000 ^{+.0005}_{-.0000}$

| ⊕ | .001 | B |

.50

$\phi 2.0000 ^{+.0005}_{-.0000}$

.50

-B-

A

1.00

8.00

8.5

.75

4 THRU THREADS #8-32
EVENLY SPACED WITH 90°
SAME ON THE OTHER SIDE OF TUBE

CROSS SECTION AT AA SHOWN IN 1:1 SCALE:

$\phi 1.75$
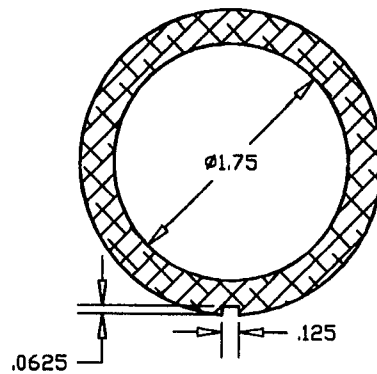
NOTES:
1. DIMENTIONS IN INCHES
2. AL. 6061-T6 TUBE, WALL THICKNESS 1/4 IN.
3. TOLERANCE ±.010 IN. IF NOT SPECIFIED
4. QUANTITY = 1

.0625

.125

| PART G |
| G01 |
| SCALE 1:2 |

.65 .85

3.00

1.285 +.000 −.003

2.75

1.00

.20 .20

1.40

⌀2.25 +.002 −.000

3 THREADS 1/4-20 X .75

5/16

.20

⌀.18

⌀.40

1.15

⌀5/16

⌀.18

⌀.625

2.25

.20 .20

1.75

.25 .90

3.00
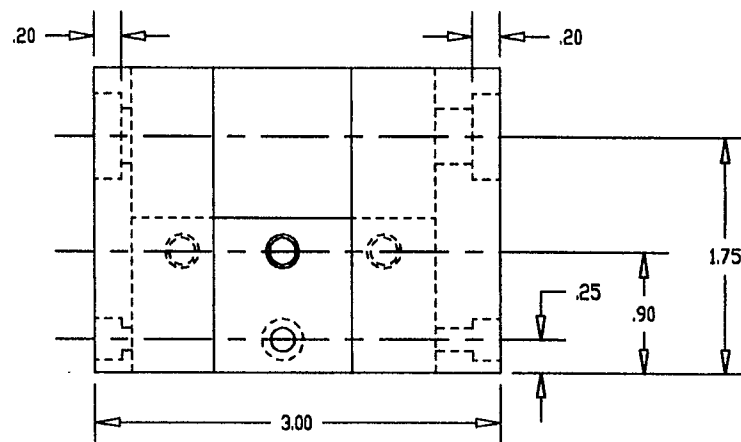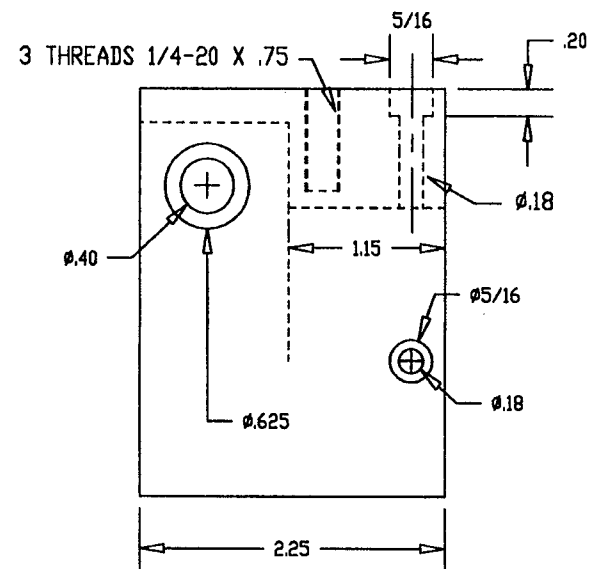
NOTES
1. DIMENTIONS IN INCHES
2. ALUMINUM − 6061 − T6
3. TOLERANCE ±.005 WHEN NOT SPECIFIED
4. QUANTITY = 1

PART G1
G11

71

FRONT VIEW OF THE SUPPORT
DETAILS ON ATTACHEMENT OF PART A
DRAWING NOT SCALE
DIMENTIONS IN INCHES

DIMENTIONS OF THE TEST SECTION SUPPORT
DIMENTIONS ARE IN INCHES
DRAWING IS NOT TO SCALE

22

3

10

28

1 5/8

4

4

10

14.5

8

4.5

.25

2.25

PART A

2 THRU HOLES IN
EACH BEAM
Ø3/8

|←| .5

|←| .75

PART F

.25

.5

PART D
PART E

PART E
PART D

.5

PART F

14.25

3.5

PART CD

PART CD

FRONT VIEW OF THE ASSEMBLY

PART C

PART C

2.125

4.5

1.25

PART C

PART C

8

TOP VIEW

5/16

.75

ø.375

1.20   1.40

1.00

ø1.005 +.005
        -.000

#8-32 UNC
2 THREADS

.875

6.00   4.500 ± .005
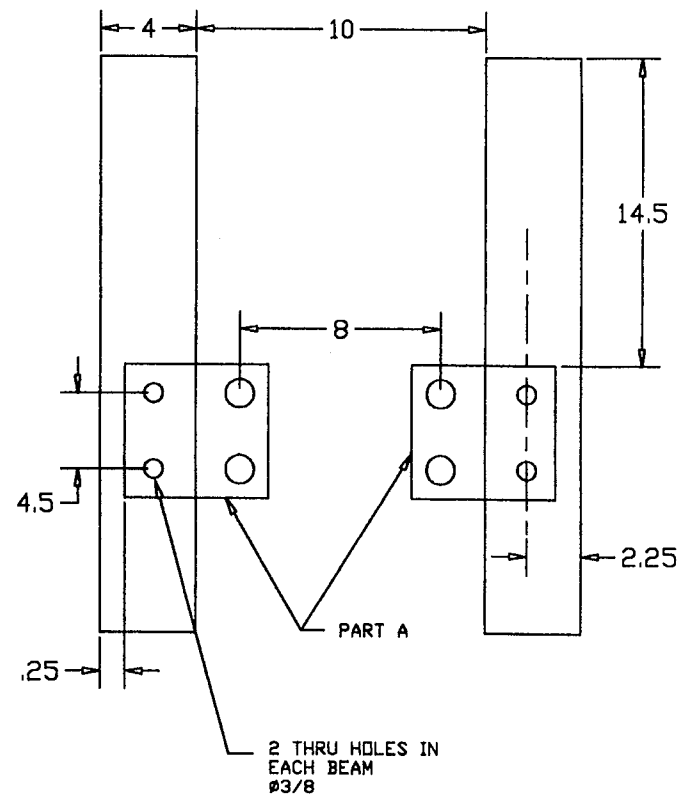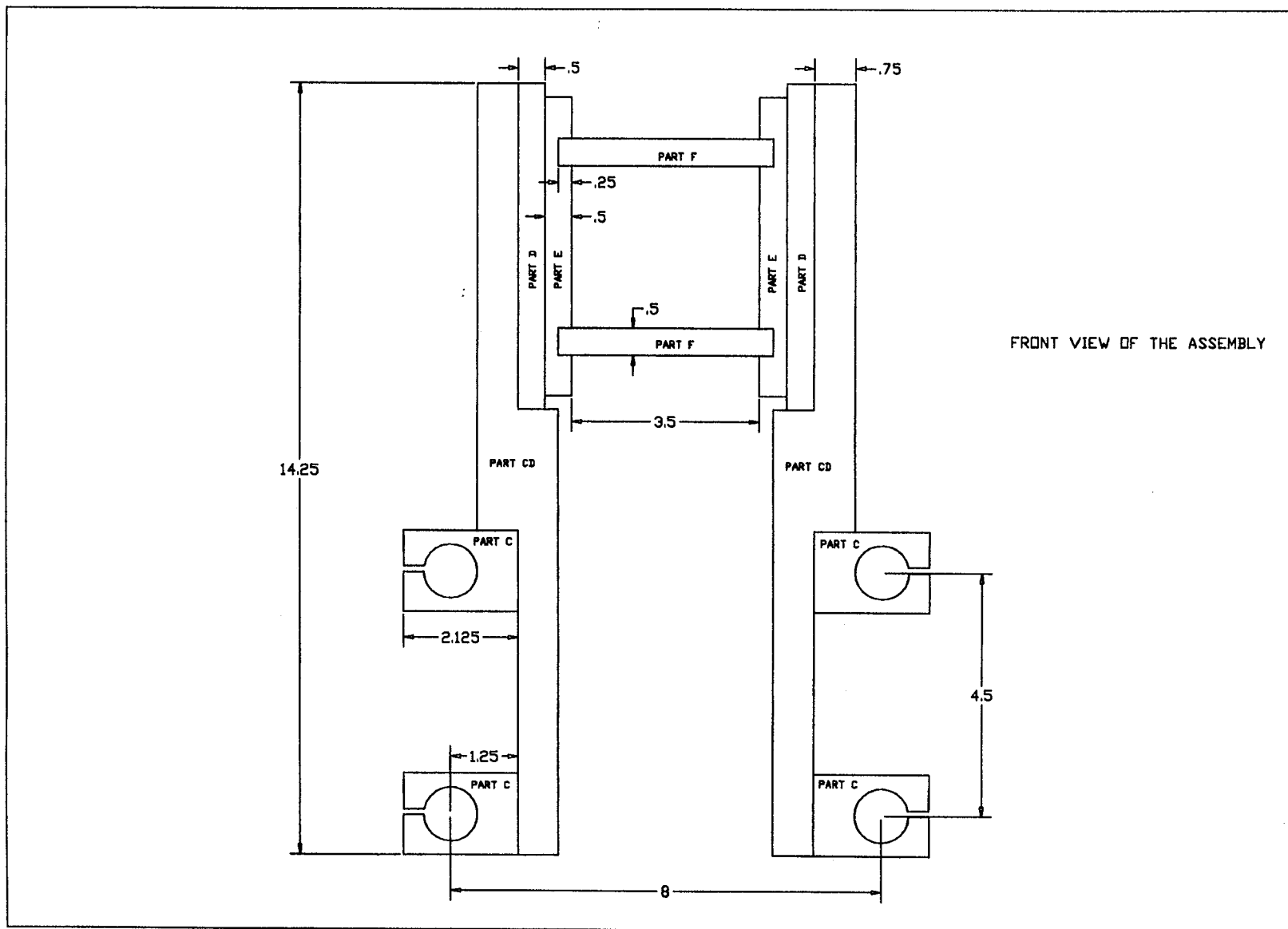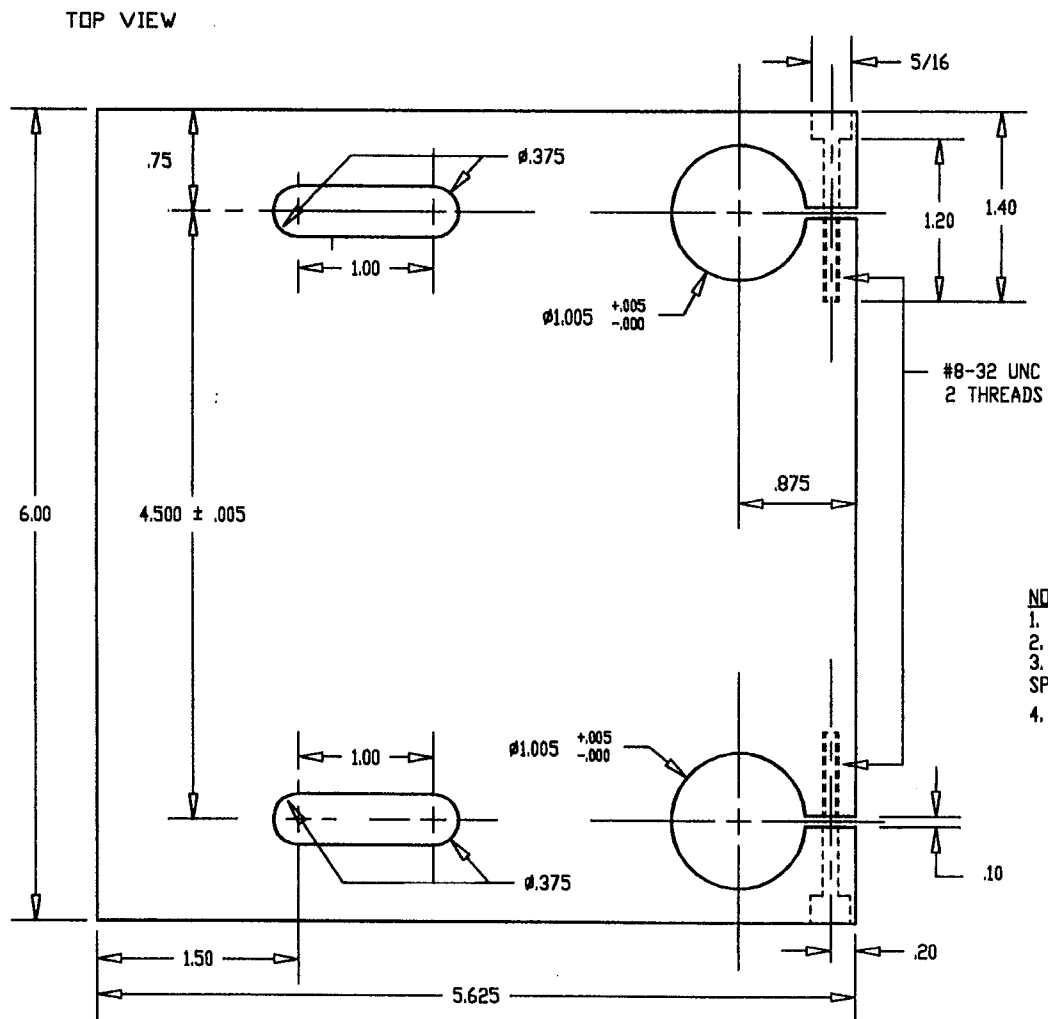
NOTES:
1. ALL DIMENSIONS IN INCHES
2. ALUMINUM – JIG PLATE 1/2 IN. THICK
3. TOLERANCE ±.010 IN. WHEN NOT
SPECIFIED

4. QUANTITY = 4

1.00   ø1.005 +.005
               -.000

.10

ø.375

1.50

.20

5.625

PART A
A01
SCALE 1:1

6

4.5

.375

.75

.75

.375

1.5

.75

.75

.75

4.5

.75

PART CD
DRAWING: PART_CD.DWG
DIMENSIONS IN INCHES
ALUMINUM 6061-T6
TOLERANCE ±.005
QUANTITY = 02

8 X ∅5/8 X .2

8 THRU THREADS #1/4-20

8 THRU HOLES ∅5/16
(REAMER)

.75

1.5

.75

1.5

3

6

14.25
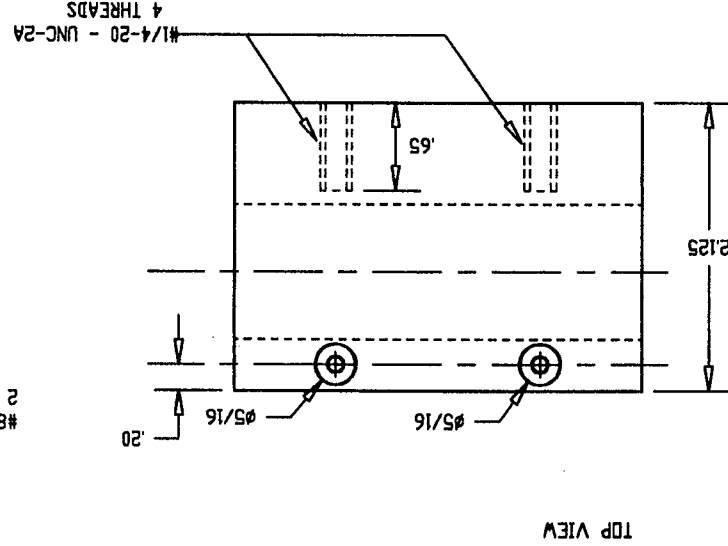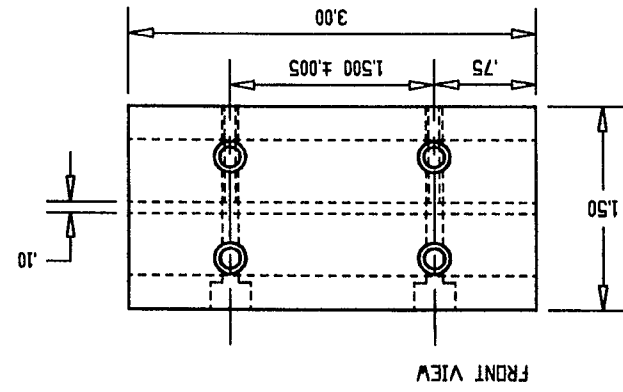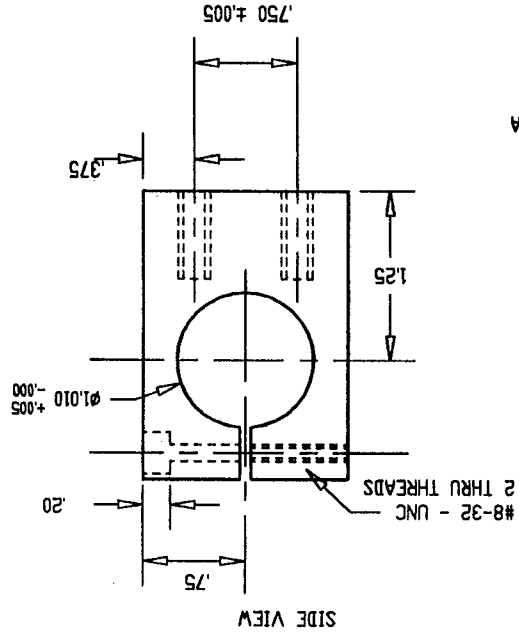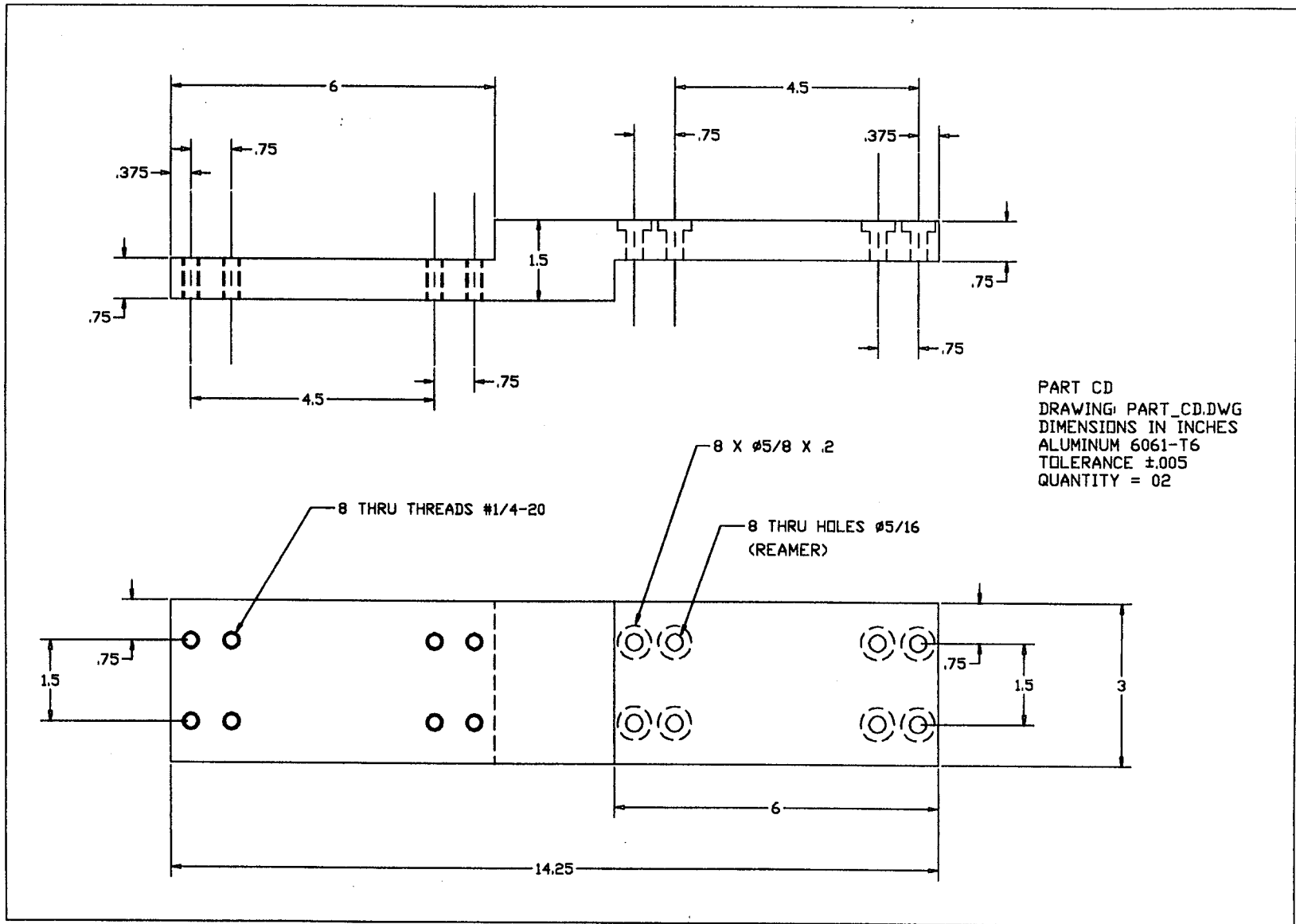
TOP VIEW

1. ALL DIMENTIONS IN INCHES
2. ALUMINUM - JIG PLATE - SEE FRONT VIEW ON DRAWING D02
3. TOLERANCE ±.010 IN. IF NOT SPECIFIED
4. QUANTITY = 2
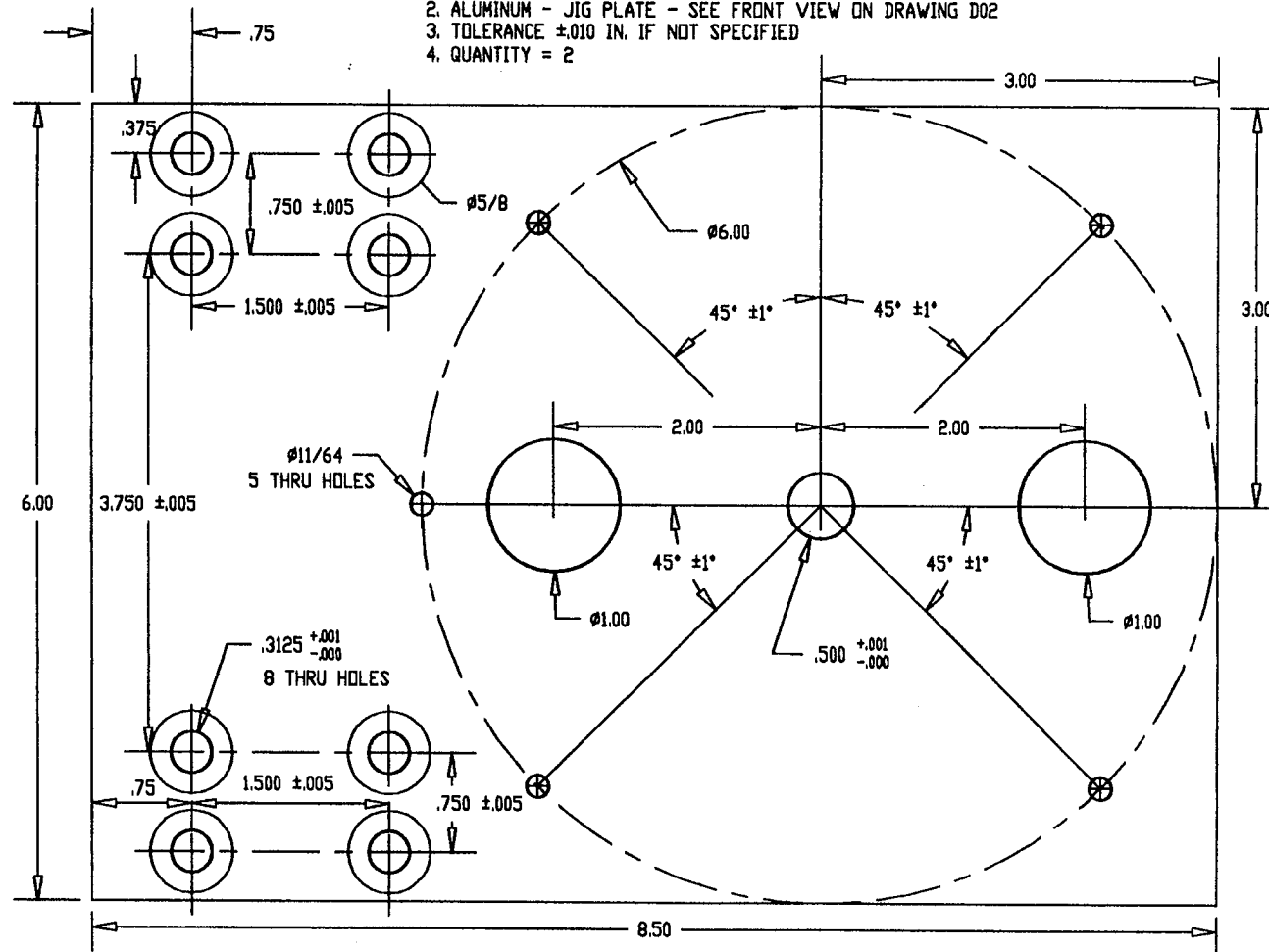
.75

.375

.750 ±.005

Ø5/8

1.500 ±.005

3.00

Ø6.00

45° ±1°   45° ±1°

2.00   2.00

Ø11/64
5 THRU HOLES

6.00   3.750 ±.005

3.00

45° ±1°   45° ±1°

Ø1.00

Ø1.00

.3125 +.001/-.000
8 THRU HOLES

.500 +.001/-.000

.75   1.500 ±.005

.750 ±.005

8.50

PART D
D01
SCALE 1:1

77

NOTES:
1. ALL DIMENSIONS IN INCHES
2. ALUMINUM - JIG PLATE
3. TOLERANCE ±.010 IF NOT SPECIFIED
4. QUANTITY = 2

FRONT VIEW

8.50

.75   1.500 ±.005   2.00   2.00

.23

.50

3.25
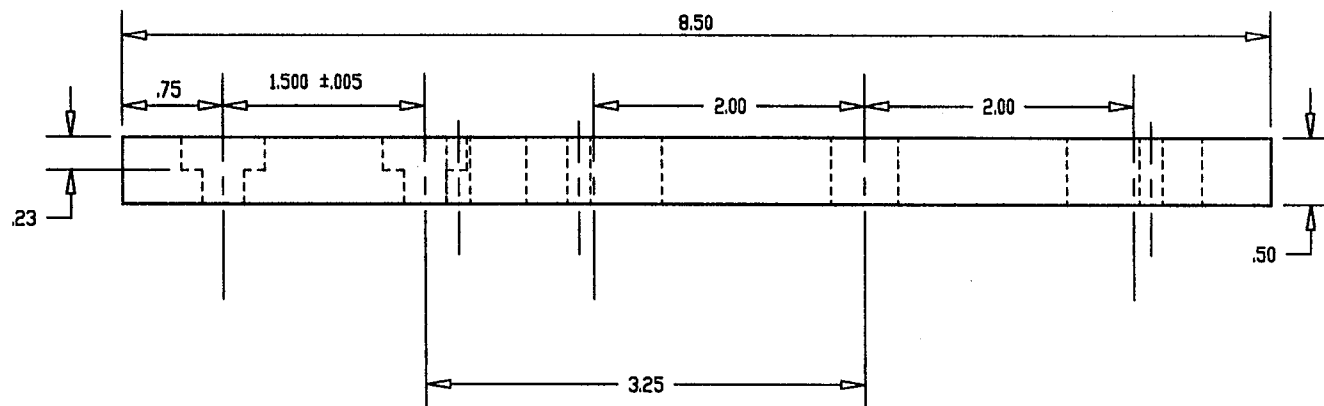
PART D
D02
SCALE 1:1

TOP VIEW

Ø5.50

Ø5/16   Ø1/8
SAME FOR THE FOUR HOLES

.500 $^{+.001}_{-.000}$

SIDE VIEW

.505 $^{+ .005}_{- .000}$

1.00

1.75

.15

1.00

FRONT VIEW

1.00

.25

.50

.50
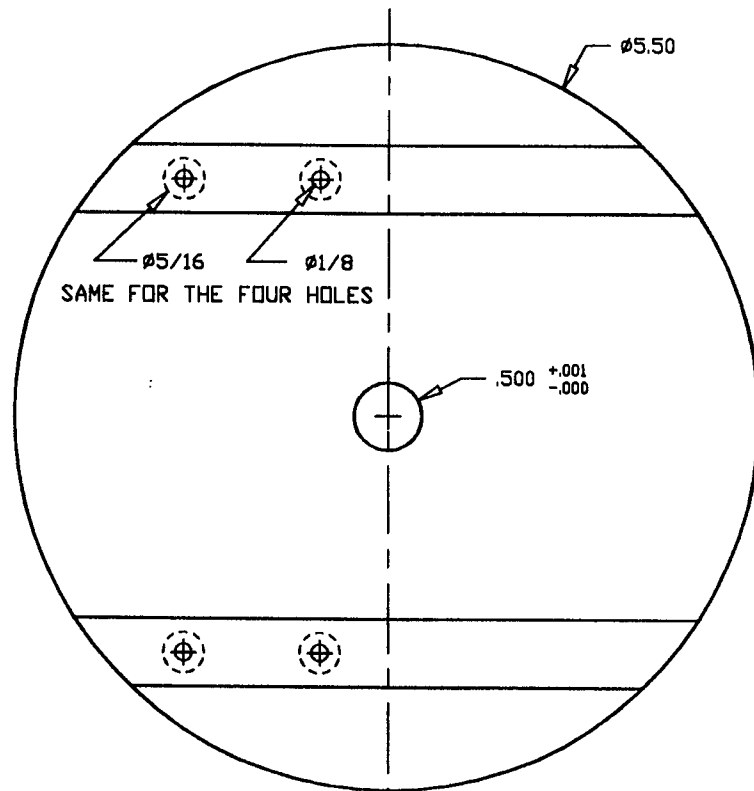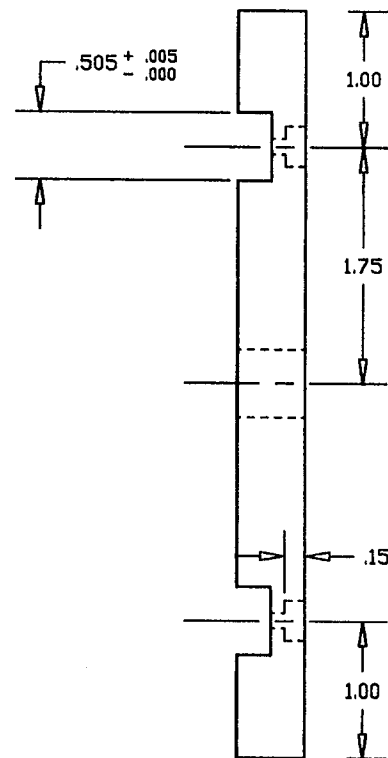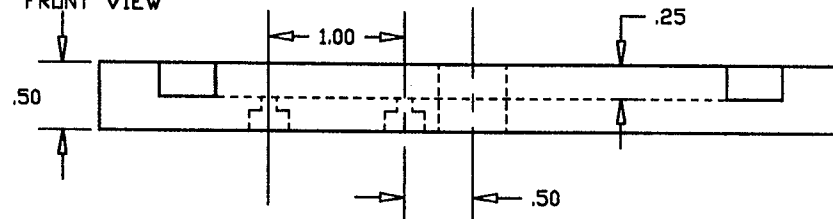
NOTES:
1. ALL DIMENSIONS IN INCHES
2. ALUMINUM - JIG PLATE
3. TOLERANCE ±.010 IN. IF NOT SPECIFIED
4. QUANTITY = 2

PART E
E01
SCALE 1:1

TOP VIEW OF THE TEST SECTION BOTTOM WALL WITH CUT OUT DETAILS

1. CUTS A AND B ARE NOT USED AND ARE CLOSED
2. CUT C ALLOWS THE ROLL SHAFT TO ENTER THE TEST SECTION
   IT IS SHOWN AT ITS MAXIMUM SIZE AND IS PARTIALLY CLOSED
   DURING EXPERIMENTS
DIMENSIONS ARE IN INCHES. TOLERANCE ±.025

REAR

C

FRONT
(INCOMING FLOW)

B

A

Ø4

R.625

R.625

6.75

5.375

9.125

4
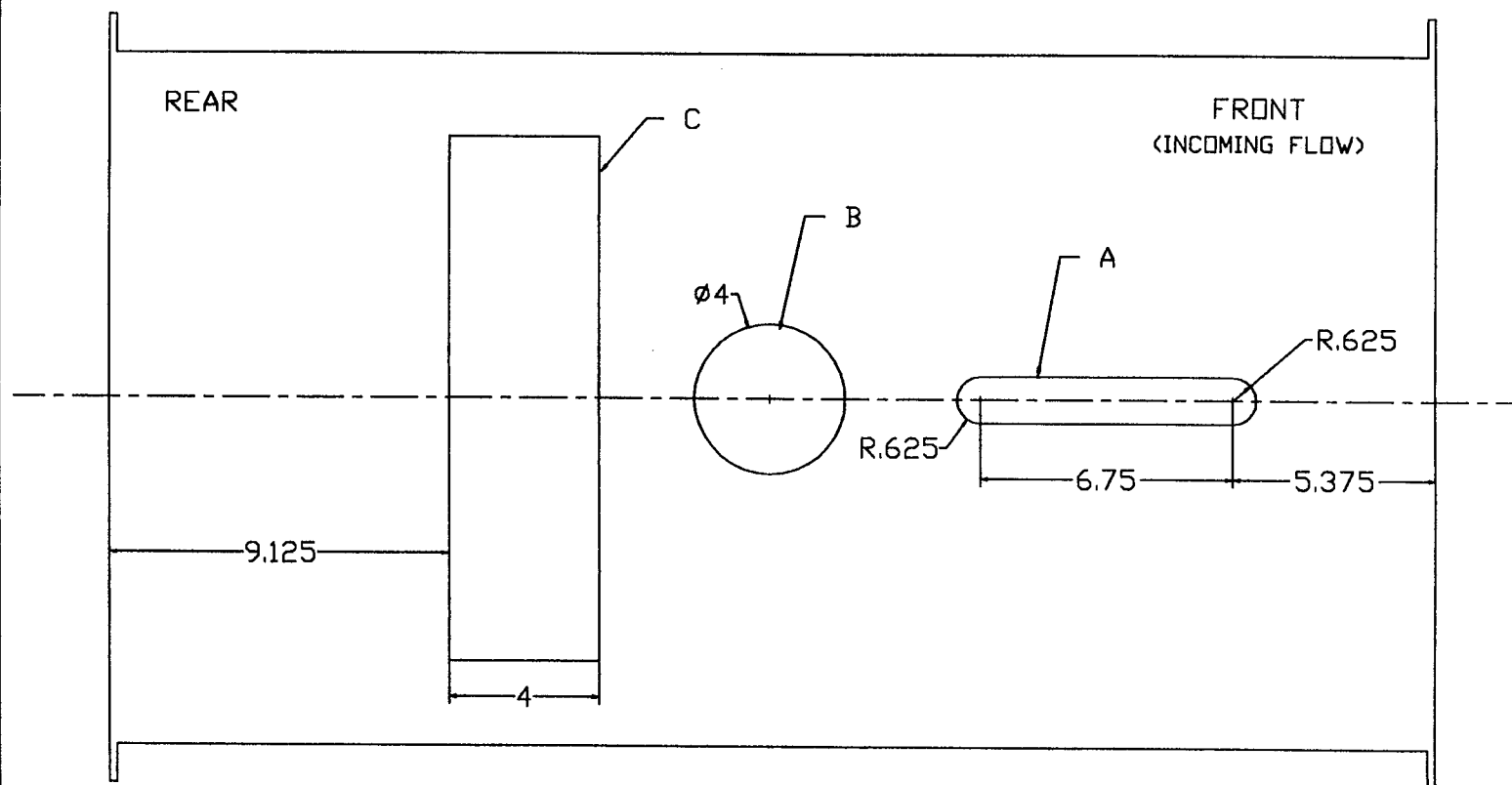
C.3   Active Cancellation Sub-system

The mechanical assembly drawing for the components of the active cancellation system is shown on Figure C.3. As seen, part YAWSYS1 connects to the yaw shaft and part YAWSYS3 to the yaw shaft support.

It is necessary to describe the location of some components not shown in the assembly drawing: The accelerometers, used to measure the angular acceleration about the γ-axis, are mounted inside the pockets of part YAWSYS2. The potentiometer, used to measure the γ angle, is mounted to part YAWSYS7 and has its axle connected to part YAWSYS2 which rotates with the yaw shaft. The 1/16 inch diameter steel cable used to connect parts YAWSYS2 and YAWSYS3 and form the 10:1 reduction.

A second assembly drawing which shows an alternate location for the accelerometers is presented in Figure C.4. It should be noted that this is an optional mounting configuration that, to date, has not been used and is included only for completeness.

ACTIVE CANCELLATION SYSTEM ASSEMBLY DRAWING

DIMENSIONS IN INCHES

YAW SHAFT SUPPORT

YAW SHAFT

YAWSYS1

YAWSYS5
(TORQUE SENSOR)

YAWSYS3

YAWSYS4

6.98

YAWSYS7

MOTOR

YAWSYS2

ELECTRO-CRAFT
S-4075-DM30

5.2
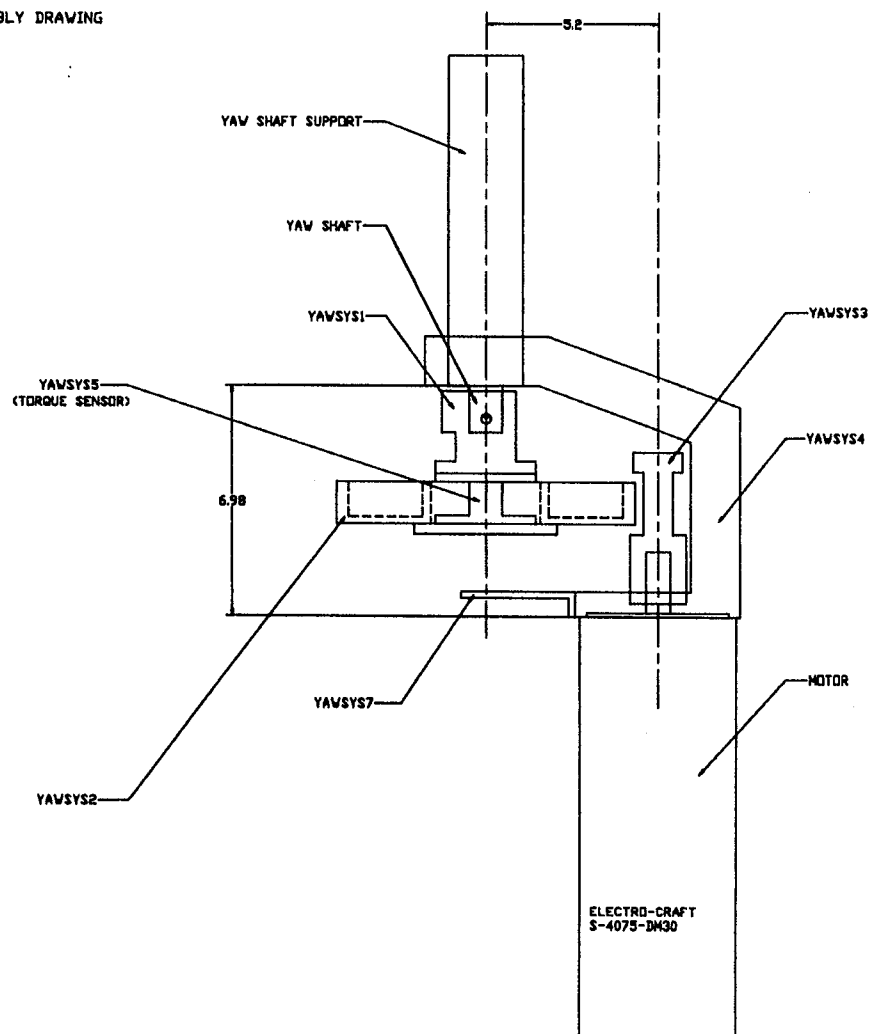
NELSON PEDREIRO
14 JAN 94
(415) 725-3297

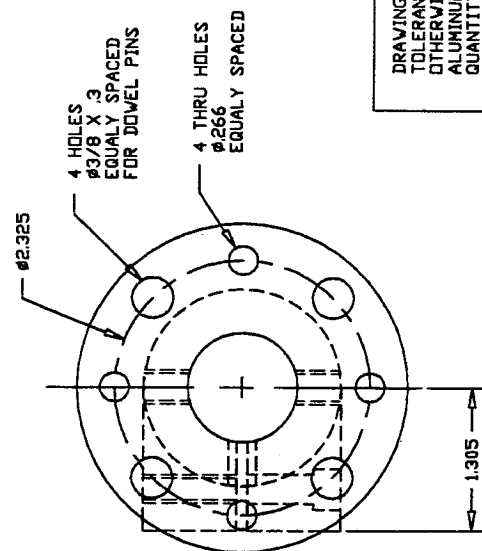Figure C.3: Active cancellation system assembly drawing.

83

ACTIVE CANCELLATION SYSTEM ASSEMBLY DRAWING

DIMENSIONS IN INCHES
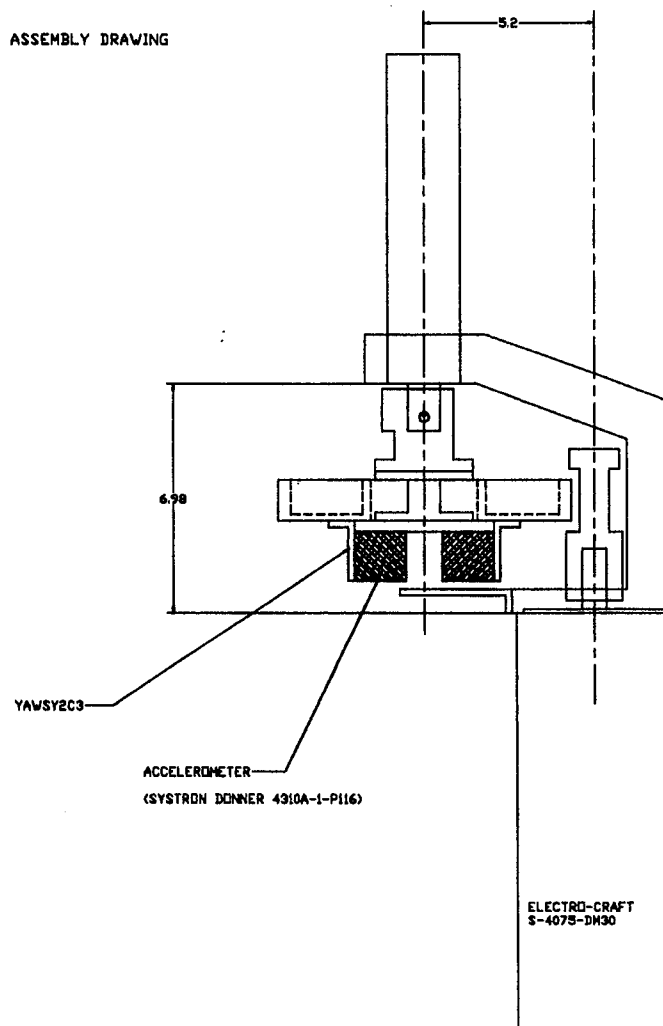
THE PREFERRED LOCATION FOR THE ACCELEROMETERS IS INSIDE THE POCKETS OF PART YAWSYS2. THEY ARE SHOWN HERE MOUNTED TO THE BOTTOM OF PART YAWSYS2 WHICH IS AN ALTERNATE LOCATION.

5.2

6.98

YAWSY2C3

ACCELEROMETER
(SYSTRON DONNER 4310A-1-P116)

ELECTRO-CRAFT
S-4075-DM30

NELSON PEDREIRO
14 JAN 94
(415) 725-3297

Figure C.4: Alternate position for accelerometers.

84

PART YAVSYS1

2 THREADS
#1/4-20

ø3/8 X 1/4

ø.266

1.25

1.8

.1

ø.25

ø3

.5563 ±.0002

ø.2500
THRU HOLE FOR
DOWEL PIN

ø.3125
THRU HOLE FOR
DOWEL PIN

2.5

.275

ø1

.325

.925

1.5

.375

4 HOLES
ø3/8 X .3
EQUALY SPACED
FOR DOWEL PINS

4 THRU HOLES
ø.266
EQUALY SPACED

ø2.325

1.305

TORQUE SENSOR MECHANICAL COMPONENT

CUT AA

4 THRU HOLES
⌀3/8
EQUALY SPACED
FOR DOWEL PINS

4 THRU THREADS
#1/4-20
EQUALY SPACED

R1/8

⌀2.325

⌀3

.25

1.5

R.25

.25

A   A

B   B

96

CUT BB

⌀3

1

.05

1

4 THRU HOLES
⌀3/8
EQUALY SPACED
FOR DOWEL PINS

⌀2.325

4 THRU THREADS
#1/4-20
EQUALY SPACED

DRAWING: FAWSYS5B
TOLERANCES ±.005 IN. UNLESS
OTHERWISE SPECIFIED
ALUMINUM 6061-T6
QUANTITY = 01

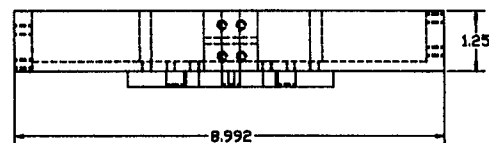NELSON PEDREIRO (415) 725-3297

PART YAWSYS2: SEE ANEXED DRAWINGS FOR DIMENSIONS
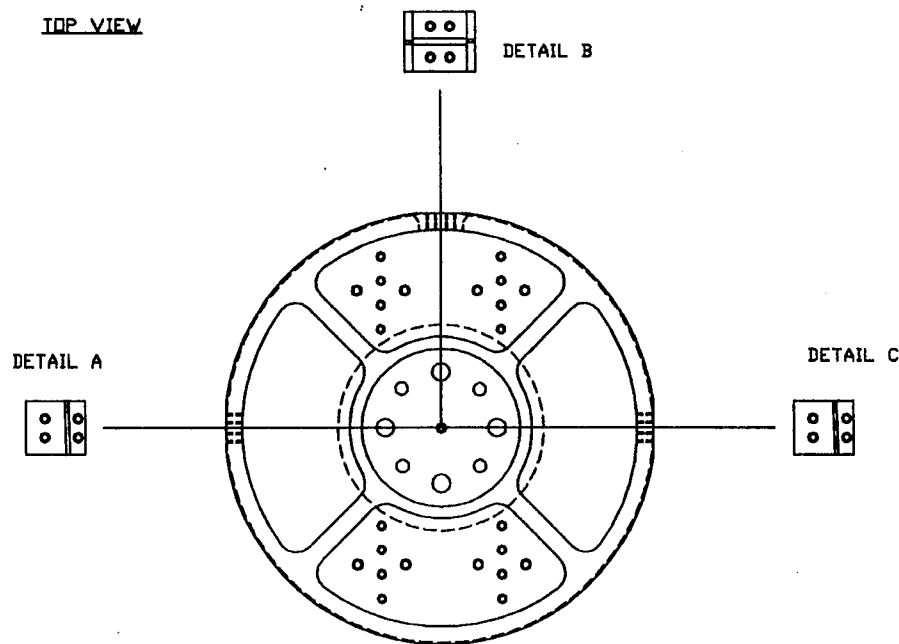
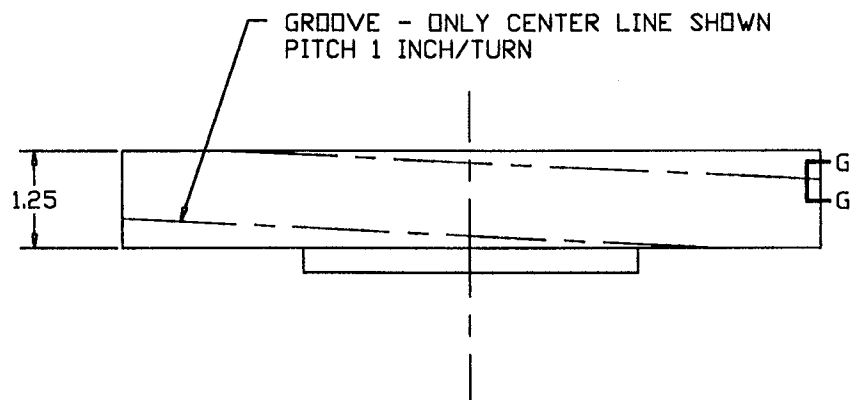FRONT VIEW: ONLY CENTER LINE OF GROOVE IS SHOWN
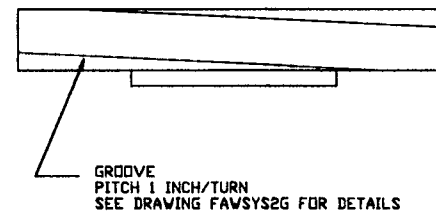
TOP VIEW

DETAIL B

GROOVE
PITCH 1 INCH/TURN
SEE DRAWING FAWSYS2G FOR DETAILS

DETAIL A

DETAIL C

87

FRONT VIEW: GROOVE NOT SHOWN

1.25

8.992

FRONT VIEW: GROOVE DETAIL

GROOVE - ONLY CENTER LINE SHOWN
PITCH 1 INCH/TURN

1.25

G
G

CUT GG

R4.5

R.035 $^{-.000}_{+.002}$

.004 $^{-.000}_{+.004}$

88

TOP VIEW

1.75

1.25

DETAIL B

.75

DETAIL A

R.375

3.55

3.05

2.85

2.55

2.05

4 HOLES
Ø3/8 X .275
EQUALLY SPACED
FOR DOWEL PINS

Ø2.325

Ø3.3

Ø3.8

THRU THREAD
#10-24

DETAIL C

4 THRU HOLES Ø.2660
EQUALY SPACED
COUNTER SINK
82° X Ø.525

Ø4.3

R.375

Ø8.992

.375

Ø8.93

TRHU THREAD
#8-32

THRU THREAD METRIC
M5 X 0,8

68

FRONT VIEW: GROOVE NOT SHOWN

1.05

1.25

1.575

Ø4.3

TOP VIEW: DETAILS A, B AND C

.2

.4

4 THREADS
#10-24 X .4

1.25

.95

.3

.127 $^{-.000}_{+.002}$

.27

R.25

.7

Ø8.992

Ø8.25

Ø8.93

.7

.4

.4

.15

.4

.2

1.25

4 THREADS
#10-24 X .4

4 THREADS
#10-24 X .4

.85
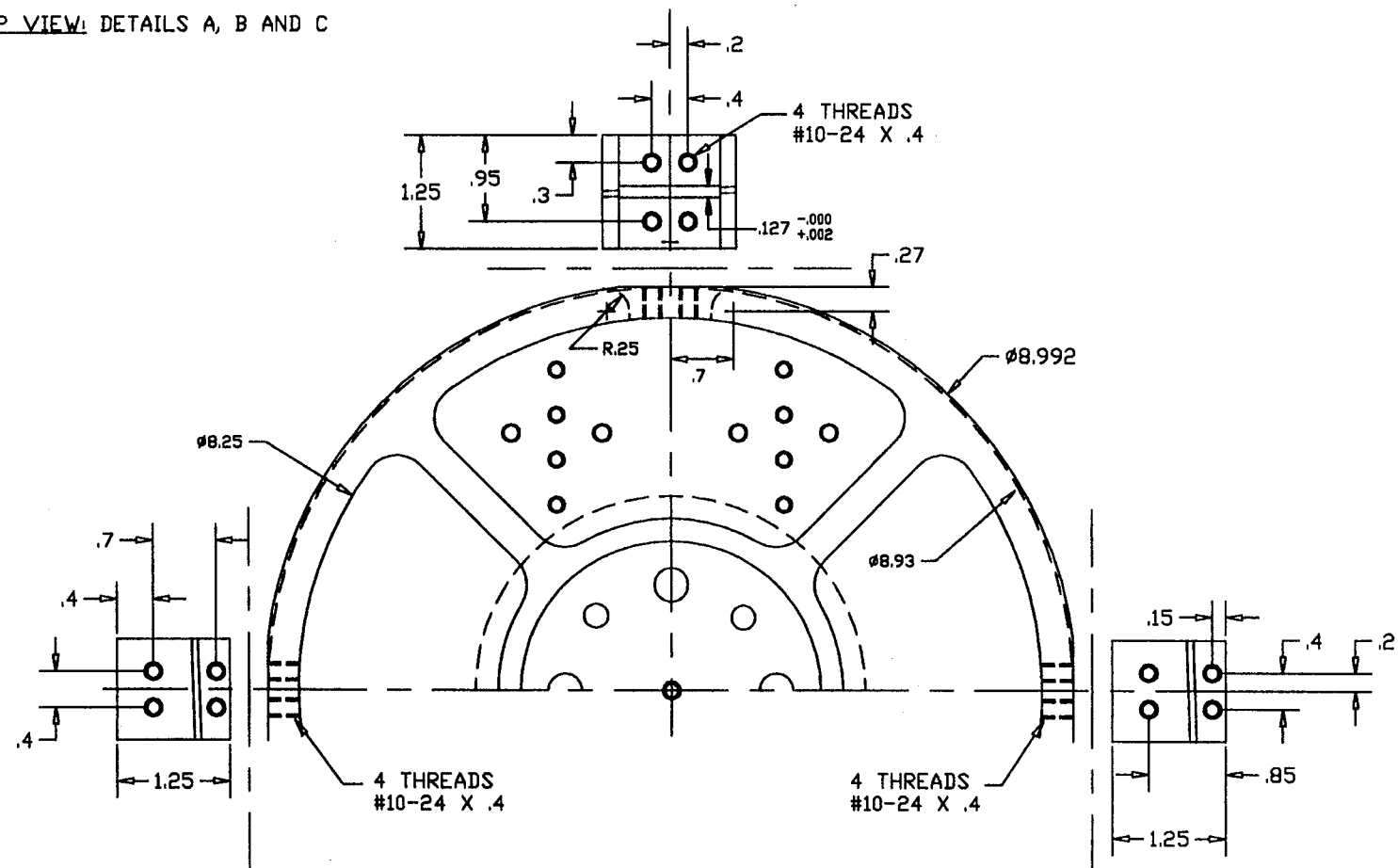
1.25

NOTE:
DETAILS A, B AND C ARE FLAT SURFACES TANGENT
TO CILINDER WITH Ø8.930 IN.

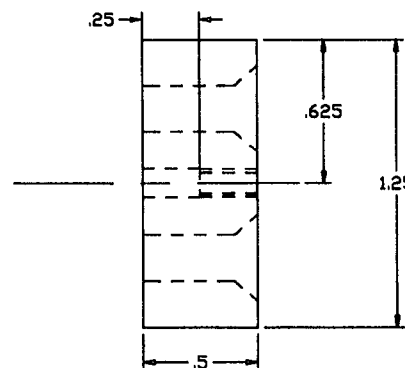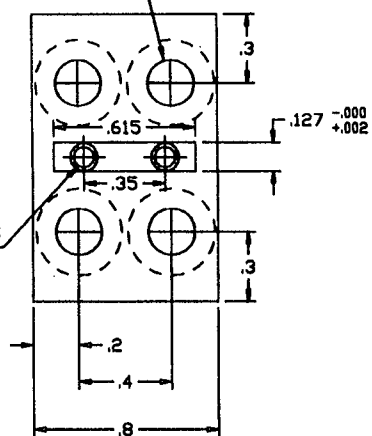DRAWING: FAWSYS2D
DIMENSIONS IN INCHES
TOLERANCES ±.005 IN.

REFER TO DRAWING FAWSYS2B

NELSON PEDREIRO (415) 725-3297

PART YAWSYS2C1 FIT PART YAWSYS2B

WOODRUFF KEY ORDERED FROM BERG
STOCK NUMBER K1-12 (p.H537)
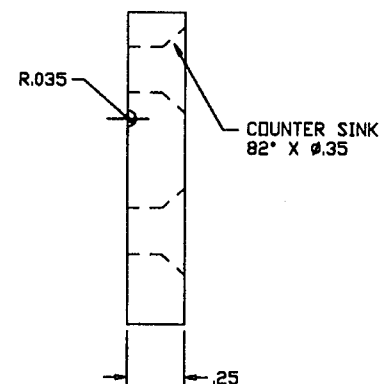
4 THRU HOLES ∅.2010 (DRILL #7)
COUNTER SINK 92° X ∅.375

.3

.615

.127 $^{-.000}_{+.002}$

.35

2 THRU THREADS
#4-40

.3

.2

.4

.8

.25

.625

1.25

.5

PART YAWSYS2C2: FIT PART YAWSYS2B

4 THRU HOLES
Ø.2010

2°   .7

R.035

COUNTER SINK
82° X Ø.35

1.35

.8609

.4

.4

.9

.25
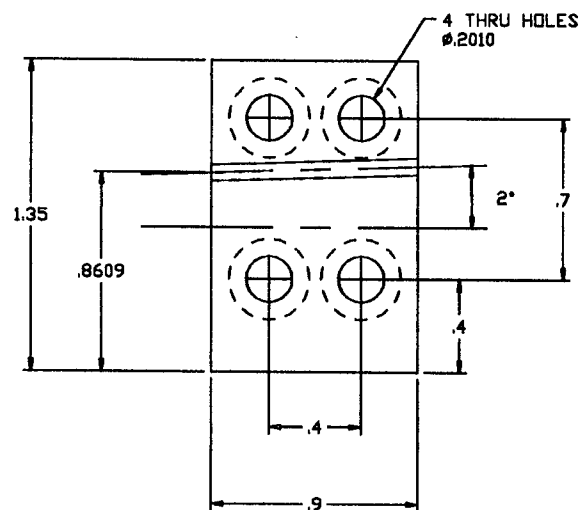
DRAWING: FAWSY2C2
DIMENSIONS IN INCHES
TOLERANCES ±.005 UNLESS
OTHERWISE SPECIFIED
ALUMINUM 6061-T6
QUANTITY = 02

NELSON PEDREIRO (415) 725-3297

.25

.4

2.5

.2

2 THRU HOLES
Ø.1695 (DRILL #18)

.5

3

.2

.6

1.075

THRU THREAD
M5 X 0,8

Ø1.25

.2

1.825

THRU THREAD METRIC
M5 X 0,8

1.25

1.25

.25

.2

3
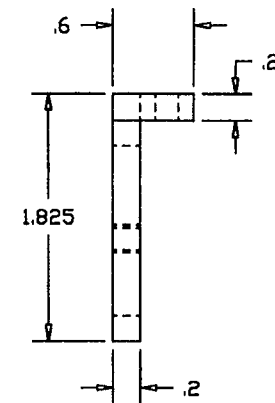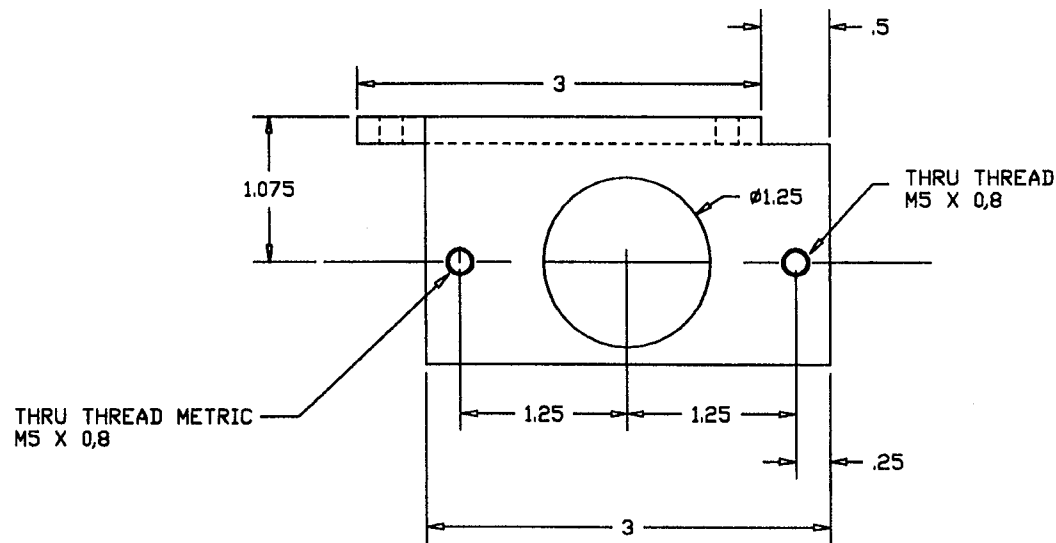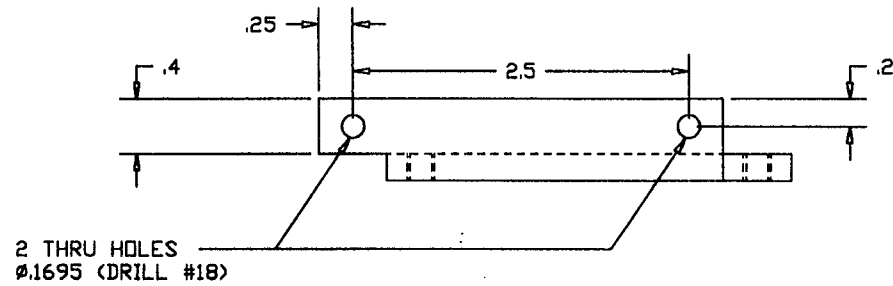
DRAWING: FAWSY2C3
DIMENSIONS IN INCHES
TOLERANCES ±.005
QUANTITY = 02
FIT PART YAWSYS2 AND ACCELEROMETER

NELSON PEDREIRO (415) 725-3297

PART YAWSYS3

SLOT FOR SQUARE KEY

Ø1.5

.28

Ø15/32 X .3 (SEE NOTE C)

THRU THREAD
#10-24

.6

.25

.057

1.9

Ø3/32

.1

2.1 1.85 1.57 1.135

.435

B

4 THRU THREADS
10-24

G

G

GROOVE - ONLY CENTER LINES ARE SHOWN
PITCH 10 TURNS/INCH
17 TURNS

SEE DRAWING FAWSYS3G
FOR GROOVE DETAILS

Ø15/32 X .4
(SEE NOTE C)

6.000 $^{-0.000}_{+0.013}$ MM

Ø1.7

21.500 $^{-0.000}_{+0.130}$ MM

A

NOTES:

A = Ø19.000 $^{-0.000}_{+0.013}$ MM

B : FIT THE SQUARE KEY PROVIDED WITH THE MOTOR
    NOMINAL 6X6X40 MM
    SEE SQUARE KEY DETAIL ABOVE

C : Ø15/32 $^{-.000}_{+.010}$
    DEEPTH MEASURED FROM HIGHEST POINT ON
    THE CIRCUNFERENCE

ANEXED DRAWINGS:	DRAWING: FAWSYS3B
FAWSYS3C FAWSYS3G	DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED MM = MILLIMETER TOLERANCES ±.005 IN. IF NOT OTHERWISE SPECIFIED ALUMINUM 6061-T6 QUANTITY = 1 NELSON PEDREIRO (415) 725-3297

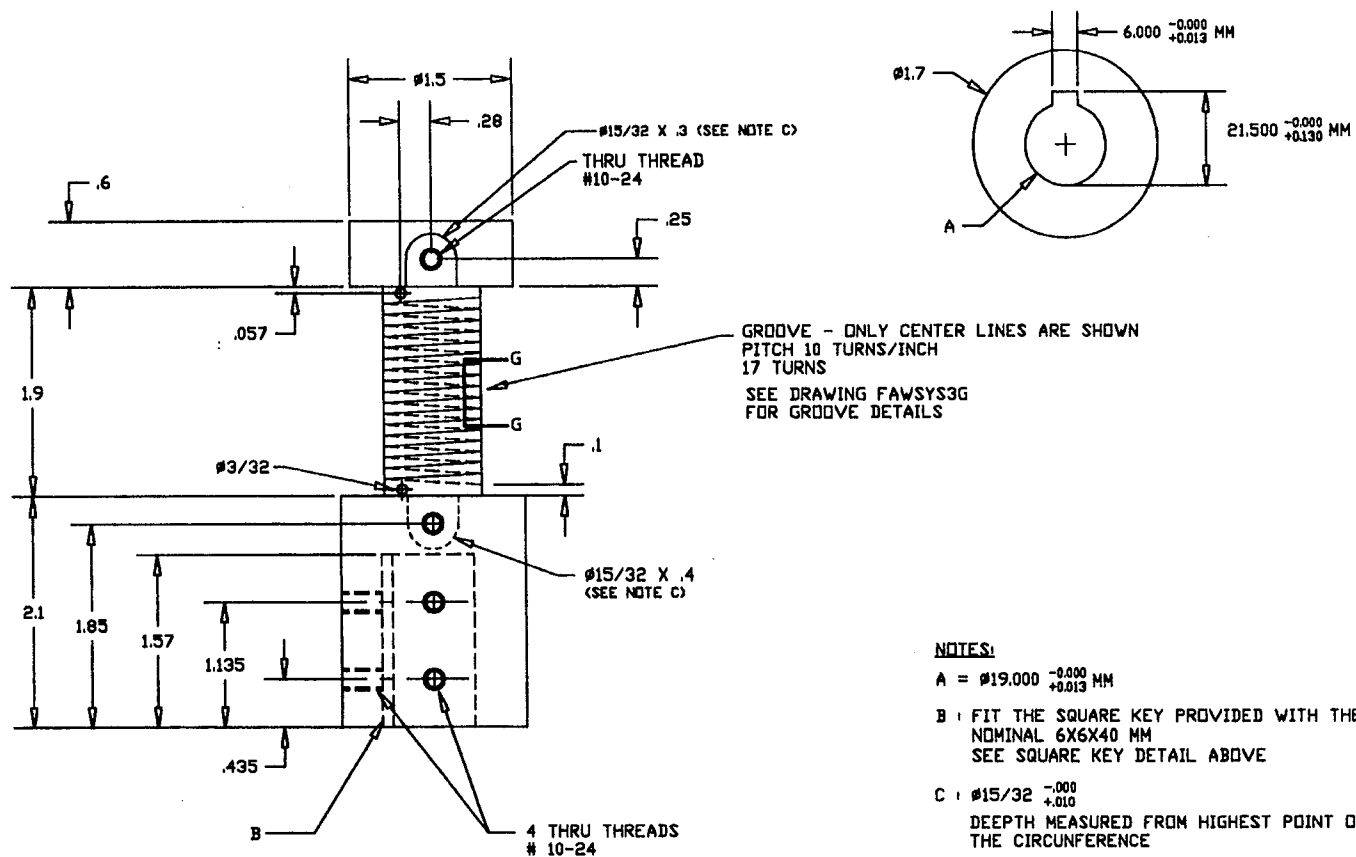GROOVE DETAIL: CUT GG FROM DRAWING FAWSYS3B

R.45

.004 $^{-.000}_{+.004}$

R.035 $^{-.000}_{+.002}$

PITCH = .1
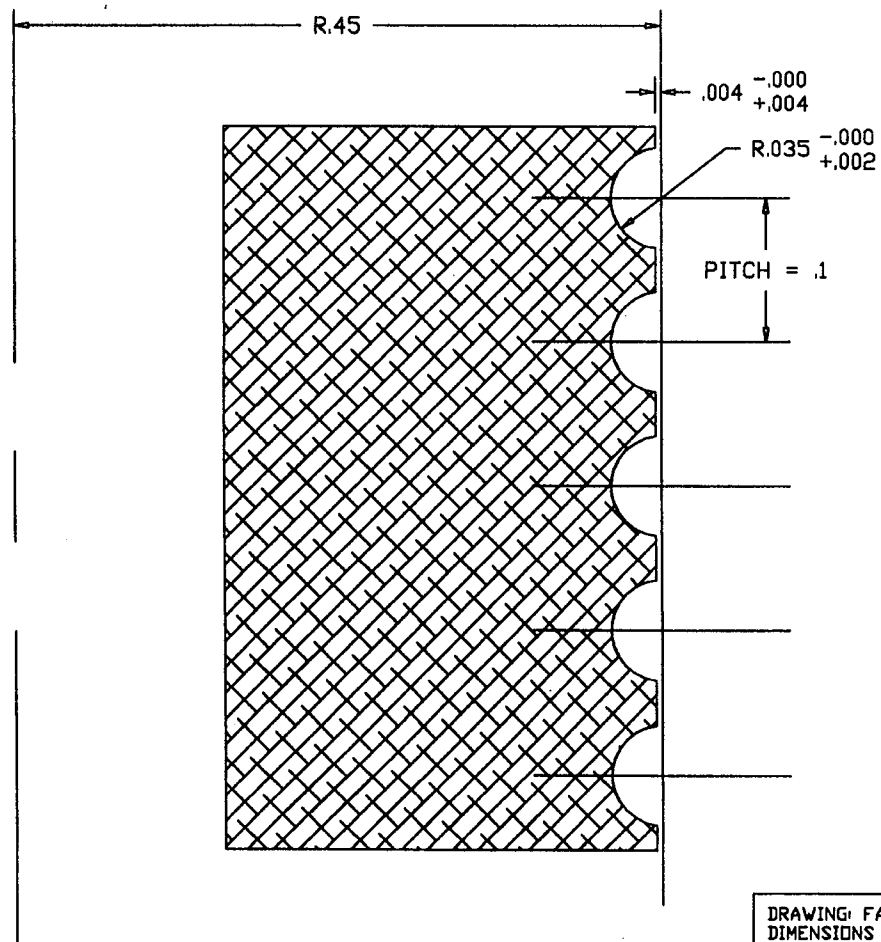
DRAWING: FAWSYS3G
DIMENSIONS IN INCHES
REFER TO DRAWING FAWSYS3B

NELSON PEDREIRO (415) 725-3297

.175

.053
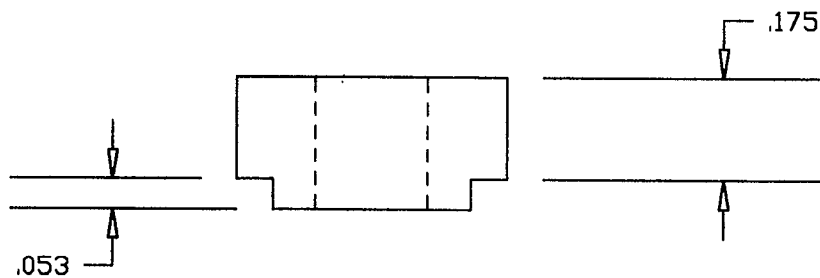
NOTES:
1. ALUMINUM 6061-T6
2. FIT PART FAWSYS3B

∅15/32 $^{-.005}_{+.000}$

∅11/32
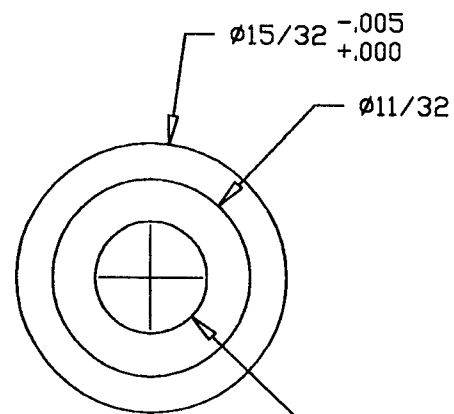
∅.1960
DRILL #9 CLOSE FIT
FOR 10-24 BOLT

DRAWING: FAWSYS3C
DIMENSIONS IN INCHES
TOLERANCES ±.005 IN IF NOT
OTHERWISE SPECIFIED
QUANTITY = 2

NELSON PEDREIRO (415) 725-3297

PART YAWSYS4

9.525

.75

1.5

.375

.45

20°

2 THRU
THREADS
#1/4-20

6.98

.1

Ø.266

Ø3/8 X 1/4

.35

Ø2.250

5.2

1.825

A   A
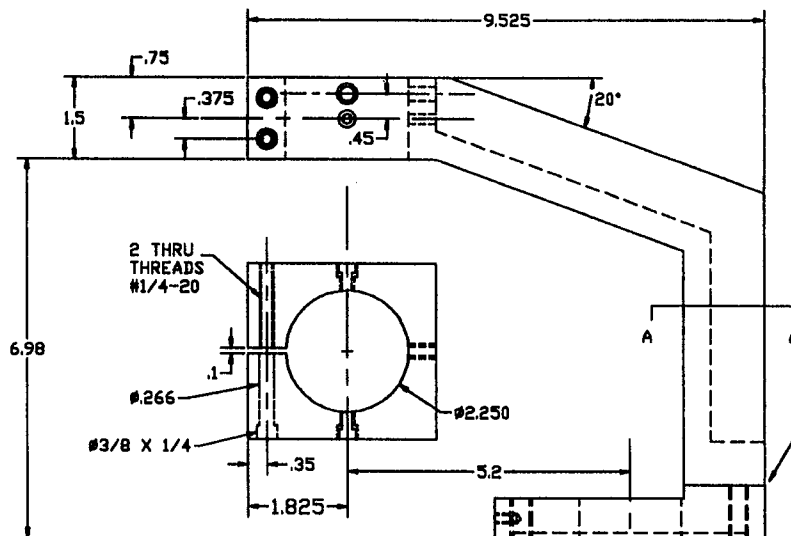
TWO PARTS
DETAILS OF
CONNECTION NOT
SHOWN.
SEE ANEXED
DRAWINGS
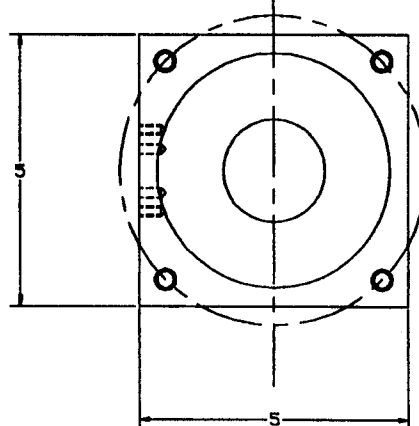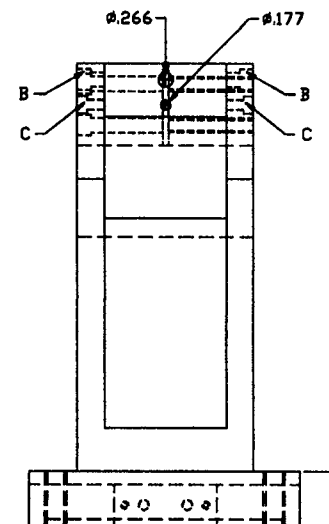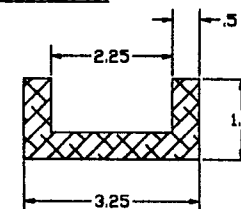
Ø.266   Ø.177

B   B

C   C

NOTES:
B. Ø.266 THRU
   Ø3/8 X 1/4

C. Ø.177 THRU
   Ø5/16 X .18

5

5

CROSS-SECTION AA

.5

2.25

1.5

3.25

ANEXED DRAWINGS:	DRAWING: FAWSYS4B
FAWSY4B1	DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED
FAWSY4B2	TOLERANCES ±.005 UNLESS OTHERWISE SPECIFIED
FAWSY4B3	ALUMINUM 6061-T6
	QUANTITY = 01
	NELSON PEDREIRO (415) 725-3297

PART FAWSY4B1

9.525

3.7145

3.45

.75

.375

1.5

2 THRU
THREADS
#1/4-20

.45

20°

.45

3.45

7.479

5.364

A   A

4.314

.8

.1

⌀.266

⌀2.250

⌀3/8 X 1/4

.35

1.825

⌀.266   ⌀.177

B   B

C   C

CROSS-SECTION AA

.5

2.25

1

1.5

3.25

.7

.45

1.375

.875

4 HOLES FOR
DOWEL PINS
⌀1/4 X .5

2 THREADS
5/16-18 X .75

.3

.9

2 THRU THREADS
5/16-18
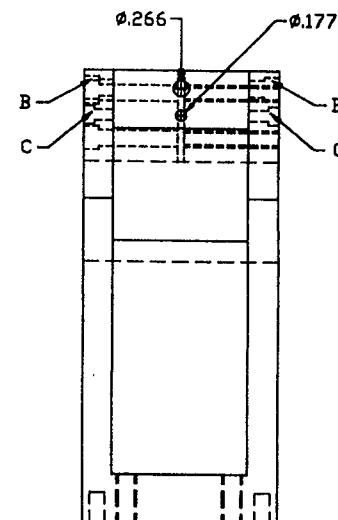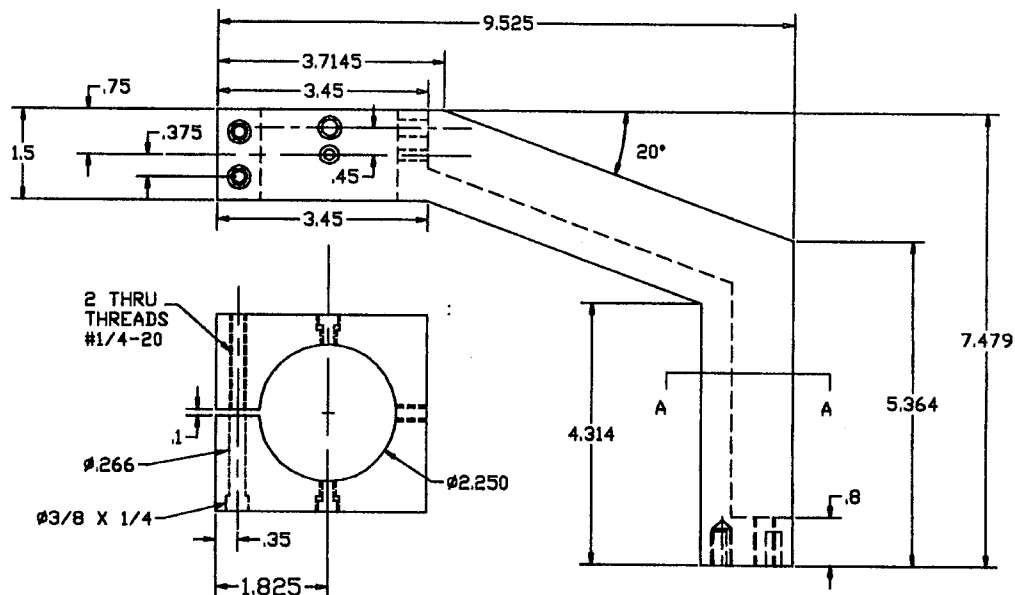
NOTES:

B. ⌀.266 THRU
⌀3/8 X 1/4

C. ⌀.177 THRU
⌀5/16 X .18

DRAWING: FAWSY4B1
DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED
TOLERANCES ±.005 UNLESS OTHERWISE SPECIFIED
ALUMINUM 6061-T6
QUANTITY = 01

NELSON PEDREIRO (415) 725-3297

66

NELSON PEDREIRO (415) 725-3297
QUANTITY = 01
ALUMINUM 6061-T6
TOLERANCES ±.005 UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED
MM = MILLIMETER
DRAWING: FAWSY4B2

3.0 MM DEEP

$\varnothing 110.000 \begin{array}{c}+0.013\\-0.000\end{array}$ MM

4 THRU THREADS #3/8-16
EQUALLY SPACED ON $\varnothing 5.71$

#8-32 X .5
THREAD

#3/16 X .5
FOR DOWEL PIN

HOLES FOR DOWEL PINS
AND BOLTS DETAILED ON
DRAWING FAWSY4B3
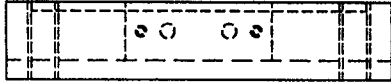
$\varnothing 1.9$

5

.75

.4

.375

.75

1.5

2.5

5

1

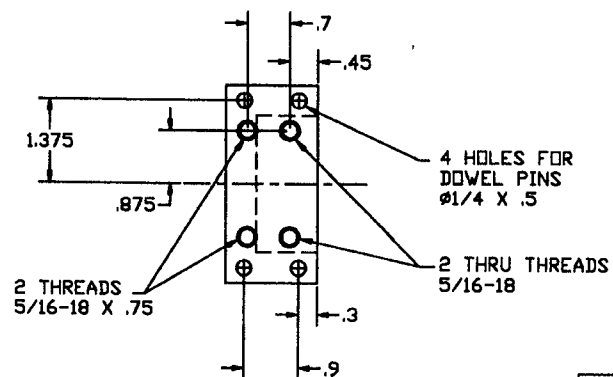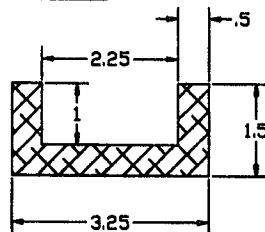PART FAWSY4B2

DRAWING: FAWSY4B3
DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED
TOLERANCES ±.005 UNLESS OTHERWISE SPECIFIED
ALUMINUM 6061-T6
QUANTITY = 01

NELSON PEDREIRO (415) 725-3297

NOTES:
DETAILED DIMENSIONS FOR DOWEL PIN HOLES
AND THRU HOLES FOR BOLTS FOR ASSEMBLY
WITH PART FAWSY4B1.
OTHER FEATURES NOT SHOWN FOR CLARITY.

.9

.3

1.375

.875

5

COUNTER SINK FOR 5/16-18
FLAT SOCKET HEAD 82°

4 THRU HOLES Ø.323 (DRILL P)
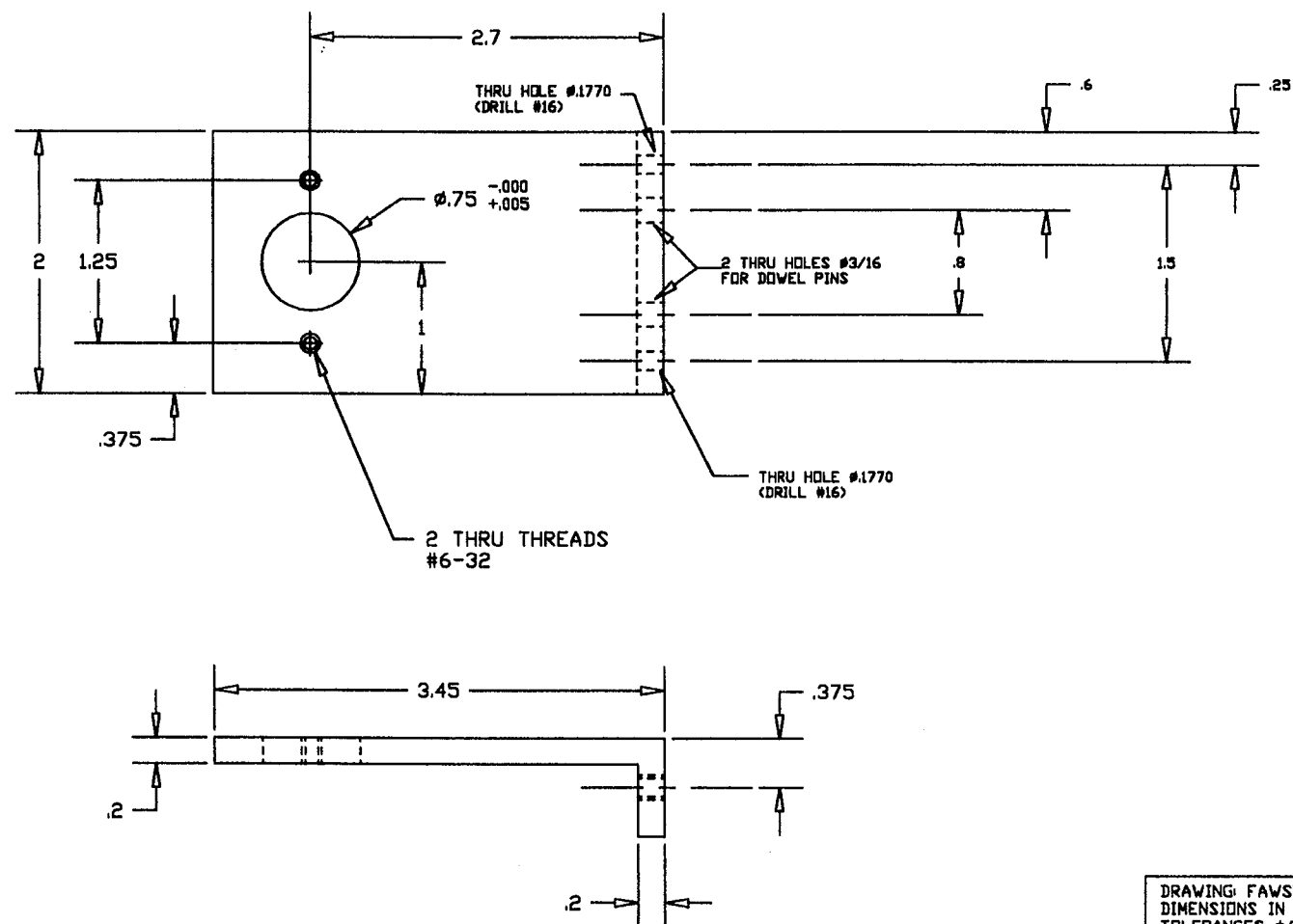
.45

4 HOLES FOR DOWEL PINS
Ø1/4 X .7

1.15

PART YAWSYS7

2.7

THRU HOLE ø.1770
(DRILL #16)

.6   .25

ø.75 -.000
      +.005

2 THRU HOLES #3/16
FOR DOWEL PINS

2   1.25   .8   1.5

1

.375

THRU HOLE ø.1770
(DRILL #16)

2 THRU THREADS
#6-32

3.45   .375

.2

.2

102

.166

.3

Ø.1495 (DRILL #25)

.4

.05

.115

.07
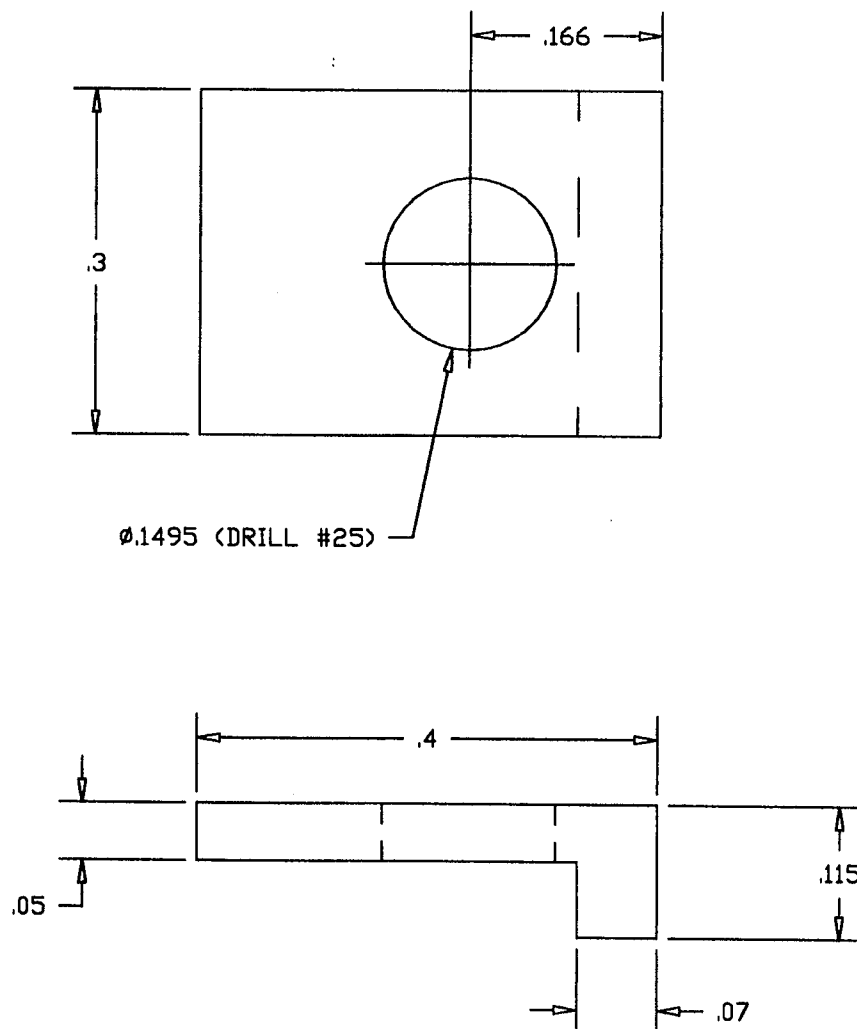
DRAWING FAWSY7B2
DIMENSIONS IN INCHES
TOLERANCES ±.005 UNLESS
OTHERWISE SPECIFIED
ALUMINUM 6061-T6
QUANTITY = 02

NELSON PEDREIRO (415) 725-3297

D   Listing of Computer Program

```
/*        program NO_GI9.C
          This program implements the inertia and gravity moment cancelation.
          The inner torque loop consists of a 2nd order (notch) compensation.

          H(s)=K.b1.b2/(ar^2+ai^2).[s^2+2.ar.s+(ar^2+ai^2)]/[s^2+2.(b1+b2).s+b1.b2]

          Discrete equivalent is obtained as follows:
          Trapezoidal Integration     s <--- 2/T *(z-1)/(z+1)

          NOTE: It is important to consider the offset of the
          torque sensor signal.

          D/A Connections: Channel 1 connect to motor drive input
          A/D Connections:
                  Channel 0 - Torque sensor output signal
                  Channel 1 - 'YAW' angle, Volts2
                  Channel 2 - Angular Acceleration, acc in Volts

          NOTES:
          1. ACC is the sum of the signals from the two accelerometers.
          The sum is done by an analog circuit. NOTE THAT NO ANALOG FILTER IS USED.
          The signal ACC after read by the A/D converter in the computer
          is filtered in this program by a 2nd order Butterworth filter:

                              1
          F(s) = _____
                      (s/w)^2 + 2*ksi*(s/w) +1

          where: w=2*pi*f
          f=cut off frequency in hertz
          ksi=0.707

          As used for the torque loop controller, a discrete equivalent is
          obtained using Trapezoidal Integration.
          287LAB assembly language I/O Subroutines
          This 287LAB example uses the A/D and D/A capabilities of
          the Data Translation DT2821-series Data Acquisition board.

          Comments:
          -Remember to use a Large memory model !!
          -Store menu options under Options-Store options.
          -Create a project file.

          Nelson Pedreiro - 31MAR95
*/
#include  <stdio.h>
#include  <conio.h>
#include  <math.h>
extern  set_clock();
extern  read_d2a();
extern  write_d2a();

char *input;
static int        gain[3] = {1, 1, 1};
static int        num_of_chan = 3;
static float      ZERO = 0.0;
static float      V2RAD = 0.099702;
static float      PI = 3.141592654;
/* Constants                                            */
/* Kts      torque sensor calibration, N.m/V            */
/* Ia       inertia of the arm in 'yaw', Kg.m^2         */
/* Kaccf    acceleration calibration, rad/s^2/V         */
static float      Kts = 6.125;
static float      Ia = 0.1589;
static float      Kaccf = 16.30;
```
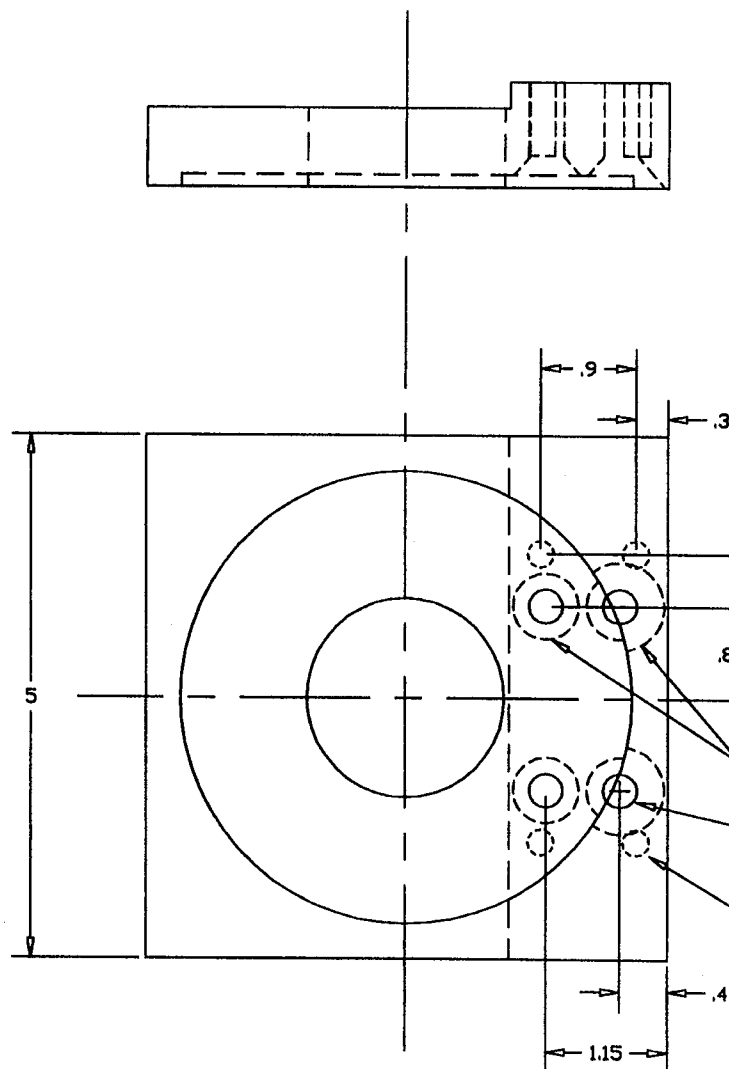
104

```c
int        sample_rate, error_flg, keypressed, exit_flg;
float      T, Vm, Vm_1, Vm_2, torque_signal, torque_offset, volts[3];
float      K, dK, ar, ai, b1, b2, cu_1, cu_2, c, c_1, c_2;
float      c0, c1, c2, d0, d1, d2;
float      KSAFE, Vm_out;
float      torque_error, torque_error_1, torque_error_2;
float      torque_cmd;
float      deadband_p, deadband_n;
float      Kg, dKg;
float      acc_offset, acc, acc_1, acc_2, ACCF, ACCF_1, ACCF_2;
float      ryaw, ryaw_1, ryaw_2, fyaw, fyaw_1, fyaw_2;
float      fn, wn, ksin, bn, acu_1, acu_2, ac, ac_1, ac_2;
float      f1, ksi1, w1, w1T, w1T2, af1, bf1, cf1, c1f1, c2f1 ;
float      f2, ksi2, w2, w2T, w2T2, af2, bf2, cf2, c1f2, c2f2 ;
float      Kiaux, Ki, alfa, dalfa;

/*************************** MAIN PROGRAM ***************************/
main()
{
torque_offset = .108;          /* Torque offset in Volts = 0.100 */
acc_offset= .000;              /* Angular Acceleration offset in Volts = .010 */

torque_offset = .100;
acc_offset= .012;

deadband_p =  0.0;             /* Motor-Drive Dead-Band */
deadband_n =  0.0;

dalfa=.025;
dKg=.01;
dK = .0;
sample_rate = 1500;
T = 1.0/sample_rate;

/* Define Torque Loop Parameters - Continuous ****************/
K=10.0;
ar = 14.5;
ai = 182;
b1 = 10;
b2 = 600;
/* Obtain Discrete Equivalent for Torque Loop ****************/
/* Auxiliary variables *************/
c0 = 4-4*ar*T+(ar*ar+ai*ai)*T*T;
c1 = 2*(ar*ar+ai*ai)*T*T-8;
c2 = 4+4*ar*T+(ar*ar+ai*ai)*T*T;
d0 = 4-2*(b1+b2)*T+b1*b2*T*T;
d1 = 2*b1*b2*T*T-8;
d2 = 4+2*(b1+b2)*T+b1*b2*T*T;
/*                      ***********/
cu_1 = -d1/d2;
cu_2 = -d0/d2;
c = c2/d2*b1*b2/(ar*ar+ai*ai);
c_1 = c1/d2*b1*b2/(ar*ar+ai*ai);
c_2 = c0/d2*b1*b2/(ar*ar+ai*ai);
/*************************************************************/
/* SPECIFY 2ND ORDER FILTER for YAW angle**************/
f1=40.0;
ksi1=0.707;

w1=2.0*PI*f1;
w1T=w1*T;
w1T2=w1T*w1T;
af1=1.0+4.0*ksi1/w1T+4.0/w1T2;
bf1=2.0-8.0/w1T2;
cf1=1.0-4.0*ksi1/w1T+4.0/w1T2;
c1f1=-bf1/af1;
c2f1=-cf1/af1;
/*************************************************************/
```

105

```
/* SPECIFY 2ND ORDER FILTER for ANGULAR ACCELERATION**********/
f2=18.0;
ksi2=0.707;

w2=2.0*PI*f2;
w2T=w2*T;
w2T2=w2T*w2T;
af2=1.0+4.0*ksi2/w2T+4.0/w2T2;
bf2=2.0-8.0/w2T2;
cf2=1.0-4.0*ksi2/w2T+4.0/w2T2;
c1f2=-bf2/af2;
c2f2=-cf2/af2;
/**************************************************************/
/* Define Parameters for NOTCH Filter - Continuous ******/
fn = 33.0;
ksin = 0.07;
wn = 2*PI*fn;
bn = wn;
/* Obtain Discrete Equivalent for Filter **********************/
ar = wn*ksin;
ai = sqrt(wn*wn-ar*ar);
b1 = bn;
b2 = bn;
/* Auxiliary variables *************/
c0 = 4-4*ar*T+(ar*ar+ai*ai)*T*T;
c1 = 2*(ar*ar+ai*ai)*T*T-8;
c2 = 4+4*ar*T+(ar*ar+ai*ai)*T*T;
d0 = 4-2*(b1+b2)*T+b1*b2*T*T;
d1 = 2*b1*b2*T*T-8;
d2 = 4+2*(b1+b2)*T+b1*b2*T*T;
/*                    ***********/
acu_1 = -d1/d2;
acu_2 = -d0/d2;
ac = c2/d2*b1*b2/(ar*ar+ai*ai);
ac_1 = c1/d2*b1*b2/(ar*ar+ai*ai);
ac_2 = c0/d2*b1*b2/(ar*ar+ai*ai);
/**************************************************************/

exit_flg = 0;
set_clock(&sample_rate);        /* Start the tick clock */
write_d2a(&ZERO,&ZERO);

do {
  system("cls");
  printf("\r\n   SAMPLING FREQUENCY = %6.2d Hz \n",sample_rate);
  printf("\r\n   Press:   Q ... to increase ALFA \r\n");
  printf("            A ... to decrease ALFA \r\n");
  printf("            P ... to increase Kg \r\n");
  printf("            L ... to decrease Kg \r\n");
  printf("\n        Z ... to set overall gain to ZERO   \r\n");
  printf("            <ENTER> ... to exit program       \r\n\n");

  printf("        Press 'G' to start. \r\n\n");
  input = getch();
  }while( toupper(input) != 'G');

printf(" PROGRAM RUNNING .... Press <ENTER> to exit. \r\n");
/* K=7  ====> Kg=.38 */
/* k=10 ====> Kg=.36 or .37 */

Kg=0.36;
alfa = 1.0;

Kiaux=Ia*Kaccf/Kts;
Ki = alfa*Kiaux;
ryaw_2 = 0.0;
ryaw_1 = 0.0;
fyaw_2 = 0.0;
```

106

```
fyaw_1 = 0.0;
ACCF_2 = 0.0;
ACCF_1 = 0.0;
acc_2 = 0.0;
acc_1 = 0.0;
Vm_2 = 0.0;
Vm_1 = 0.0;
torque_error_2 = 0.0;
torque_error_1 = 0.0;
KSAFE = 1.0;
do {
  printf("K = %5.2f    Kg = %6.3f    Alfa= %6.3f \n", K, Kg, alfa);
  /*****************************************************************/
  do {
    read_a2d(&num_of_chan,gain,volts,&error_flg);
    torque_signal = volts[0];
    ryaw= -volts[1];
    acc = volts[2] - acc_offset;
/* 2ND ORDER BUTTERWORTH FILTER FOR YAW ANGLE */
/*    fyaw=(ryaw+2.0*ryaw_1+ryaw_2)/af1+c1f1*fyaw_1+c2f1*fyaw_2; */
    fyaw=ryaw;
/* 2ND ORDER BUTTERWORTH FILTER FOR ANGULAR ACCELERATION */
    ACCF=(acc+2.0*acc_1+acc_2)/af2+c1f2*ACCF_1+c2f2*ACCF_2;
/* NOTCH FILTER FOR ANGULAR ACCELERATION */
/*    ACCF = acu_1*ACCF_1 + acu_2*ACCF_2 + ac*acc + ac_1*acc_1 + ac_2*acc_2; */
    torque_cmd = -Ki*ACCF + Kg*sin(V2RAD*fyaw);
    torque_error = torque_cmd - (torque_signal - torque_offset);
    Vm = cu_1*Vm_1 + cu_2*Vm_2 + K*(c*torque_error + c_1*torque_error_1 + c_2*torque_error_2);
    Vm = KSAFE*Vm;
    if( fabs(Vm)-fabs(Vm_1)  > 2 ) { Vm = Vm_1; }

    ryaw_2 = ryaw_1;
    ryaw_1 = ryaw;
    fyaw_2 = fyaw_1;
    fyaw_1 = fyaw;
    ACCF_2 = ACCF_1;
    ACCF_1 = ACCF;
    acc_2 = acc_1;
    acc_1 = acc;

    Vm_2 = Vm_1;
    Vm_1 = Vm;
    torque_error_2 = torque_error_1;
    torque_error_1 = torque_error;

    Vm_out = Vm;
    if(Vm>0.015) { Vm_out = Vm +deadband_p; }
    if(Vm<0.015) { Vm_out = Vm +deadband_n; }

    /***** SAFETY CLAUSE *****/
    if( Vm_out > 2.0 ) {
      Vm_out = .1;
          printf(" Safety Clause - Output Exceeds 2V \n");
          }
    if( Vm_out < -2.0 ) {
      Vm_out = -.1;
          printf(" Safety Clause - Output Exceeds 2V \n");
          }

    /***** SAFETY CLAUSE *****/
    if( fyaw > 6.0 ) {
      Vm_out = 0.0;
          KSAFE=0.0;
          printf(" Safety Clause - 'YAW' Angle Exceeds 6V \n");
          }
    if( fyaw < -6.0 ) {
      Vm_out = 0.0;
```

```c
                    KSAFE=0.0;
                    printf(" Safety Clause - 'YAW' Angle Exceeds 6V \n");
                    }

        write_d2a(&ZERO, &Vm_out);

        keypressed = kbhit();
        } while (keypressed==0 );
/*****************************************************************/

    input = getch();
    switch( toupper(input) ) {
        case 'Q':
                alfa = alfa + dalfa;
                Ki = alfa*Kiaux;
                break;
        case 'A':
                alfa = alfa - dalfa;
                Ki = alfa*Kiaux;
                break;
        case 'P':
                Kg = Kg + dKg;
                break;
        case 'L':
                Kg = Kg - dKg;
                break;
        case 'Z':
                K = 0.0;
                break;
        case '\r':
                exit_flg = 1;
                break;
        }
    } while( exit_flg == 0 );

write_d2a(&ZERO,&ZERO);

if(error_flg != 0) {
    printf("\n ******  SAMPLE RATE IS TOO FAST!!! ******");
    exit(1);
    }

if(error_flg == 0) {
    printf("\n   SAMPLE RATE IS OK");
    }

}
/*********************** END OF MAIN PROGRAM ***********************/
```

References

[1] Skow, A.M., Moore, W.A., and Lorincz, D.J., "Forebody Vortex Blowing - A Novel Control Concept to Enhance Departure/Spin Recovery Characteristics of Fighter and Trainer Aircraft", AGARD CP-262, No. 24, pp. 24-1 to 24-17, May 1979.

[2] Ericsson, L.E. and Reding, J.P., "Alleviation of Vortex Induced Asymmetric Loads", Journal of Spacecraft and Rockets, Vol 17, Nov.-Dec. 1980, pp. 546-553.

[3] Rao, D.M., Moskovitz, C., and Murri, D.G., "Forebody Vortex Management for Yaw Control at High Angles of Attack," Journal of Aircraft, Vol. 24, No. 4, p. 248-254, April 1987.

[4] Ng, T.T., and Malcolm, G.N., "Aerodynamic Control Using Forebody Strakes," AIAA Paper 91-0618.

[5] Adams, R.J., Buffington, J.M., and Banda, S. S., "Active Vortex Flow Control for VISTA F-16 Envelope Expansion," AIAA Paper 94-3681.

[6] Mittelman, Z., and Kroo, I., "Unsteady Aerodynamics and Control of Delta Wings with Tangential Leading-Edge Blowing," AIAA Paper 89-3374.

[7] Wood, N.J., Roberts, L., and Celik, Z.Z., "Control of Asymmetric Vortical Flows over Delta Wings at High Angles of Attack," Journal of Aircraft, Vol. 27, No. 5, May 1990.

[8] Font, G.I., Celik, Z.Z., and Roberts, L., "A Numerical and Experimental Study of Tangential Jet Blowing Applied to Bodies at High Angles of Attack," AIAA Paper 91-3253.

[9] Wong, G.S., "Experiments in the Control of Wing Rock at High Angles of Attack Using Tangential Leading Edge Blowing," Ph.D. Dissertation, Department of Aeronautics and Astronautics, Stanford University, 1992.

[10] Celik, Z.Z. and Roberts, L., "Vortical Flow Control on a Wing-Body Combination Using Tangential Blowing," AIAA Paper 92-4430.

[11] Celik, Z.Z., Roberts, L. and Pedreiro, N., "The Control of Wing Rock by Forebody Blowing," AIAA Paper 93-3685.

[12] Celik, Z.Z., and Roberts, L., "Vortical Flow Control on a Delta Wing by Lateral Blowing," AIAA Paper 94-0509.

[13] Hong, J.S., "A theoretical and Computational Study on the Effects of Leading Edge Lateral Blowing on Delta Wing Aerodynamics," Ph.D. Dissertation, Department of Aeronautics and Astronautics, Stanford University, 1994.

[14] Celik, Z.Z., Roberts, L. and Pedreiro, N., "Dynamic Roll and Yaw Control by Tangential Forebody Blowing," AIAA Paper 94-1853.

[15] Pedreiro, N., Rock, S.M., Celik, Z.Z. and, Roberts, L., "Roll-Yaw Control at High Angle of Attack by Forebody Tangential Blowing," AIAA Paper 96-0773.

[16] Pedreiro, N., "Experiments in Aircraft Roll-Yaw Control Using Forebody Tangential Blowing," Ph.D. Dissertation, Department of Aeronautics and Astronautics, Stanford University (to be published).

[17] Sensors Designer's Handbook and Catalog, New England Instrument, 245 Railroad Street, Woonsocket, RI 02895-1129, USA.

[18] Kulite Semiconductor Strain Gage Manual, Kulite Semiconductor Products, Inc., One Willow Tree Road, Leonia, New Jersey 07605, USA.

[19] Installation and Operations Manual for F/T, (Manual PN 9610-05-1001-09, Software version 4.25), Assurance Technologies, Inc. 503D Highway 70 East, Garner, North Carolina 27529, USA.

[20] Electro-Craft® Servo Systems - BRU-200, BRU-500 Brushless Drives Instruction Manual, Reliance Motion Control, Inc., 6950 Washington Avenue South, Eden Prairie, Minnesota 55344, USA.

[21] Ims, S.D., "Inertia Measuring System," ARL Memo 75, July 29 1991. Stanford Aerospace Robotics Laboratory.